Department of Computer Science

Designing Large Shape Changing Infrastructures

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Master of Science in the Faculty of Engineering

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Declaration:

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of Master of Science in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

Jiayi Hong, July 2019

1. EXECUTIVE SUMMARY

Walls make up the majority of a building's surface area, but in most cases, they are static, thus being limited to the unique function of separating spaces. Though wall displays enable walls to deliver more information, they lost the intuitiveness of tangible objects. As shown in some artworks, with shape-changing abilities, walls could change their shapes and contribute to the adaptive environment. However, there is a limited understanding of how to interact with such systems and how they could enrich experience in the context of a smart home. Therefore, in this project, I propose to explore the intuitive interaction thus to enhance user experiences within smart homes. There has already been some work towards creating shape-changing surfaces of small size devices (e.g. handheld display) and understanding how to enhance the communication between them. Nonetheless, most of the investigations had remained to research on gestures. Thus, to achieve the goal, I conducted a total of 3 studies: the first was three ideation workshops (N=9) and the goal was to gather promising functions; the second was an elicitation study (N=20) and the goal was to investigate how people would deal with the system input; the third one was a design session (N=6) whose aim was to explore people's attitudes towards the feedback of the system. Recommendations of gestures design were given. At last, to prove the concept, I designed the structure, adopted 3D printing technology and used Arduino along with stepper motors to develop a small-scale mock-up.

The contribution of the study are:

- The idea generation of the shape-changing walls' applications.
- The investigation about how end-users would interact with the shape-changing wall system and what feedback they would expect to get.
- The implementation of a low-fidelity wall system.

Acknowledgments

First of all, I would like to thank the University of Bristol for offering me the opportunity to pursue my interested topic. In addition, I would like to give a special thanks to my supervisor Anne Roudaut for providing valuable suggestions. And finally, I would like to thank my friends and my family who supported me in the whole process. I look forward to pursuing the further study in Computer Science.

CONTENT

2. CHAPTER 1: INTRODUCTION AND PROJECT AIM

2.1 Introduction

Walls are everywhere separating the space and supporting the architecture of all of our buildings. As the space in a modern building is getting scarcer, extending the functions of walls could become valuable. Attaching large-sized displays on walls is one approach that has been proposed (Ball *et al.*, 2007; Liu *et al.*, 2014; Liu *et al.*, 2017). In this way, these displays deliver additional information to the people in the vicinity. It also enables new types of interaction with them (Fran *et al.*, 2001; Cheung e Scott, 2013; Nutsi, 2015; Liu *et al.*, 2017; Mojgan *et al.*, 2018). Such interactive walls also offer the advantages of supporting interaction with multiple users at the time (Wu e Balakrishnan, 2003; Vogel e Balakrishnan, 2004). In order to explore other possibilities that walls could have except the function to display two-dimensional information, a number of researchers attempted to contribute to smart homes with the help of walls (Kim *et al.*, 2011; Zhang *et al.*, 2018; Hsu *et al.*, 2019). In these cases, walls served as an input receiver and collected users' behavioural data. However, the feedback had to rely on other appliances, such as tabletop interfaces and mobile phones, rather than walls themselves.

These projects on interactive walls were an inspiration to this work and here I want to push the research boundary further. I suggest that the walls could also directly and independently send feedbacks to users via shape-changing properties. For example, the wall could deform to indicate users new functionalities. This work thus also take inspirations from the shape-changing interfaces which have the benefit of maintaining the intuitiveness of tangible interfaces(Ishii e Ullmer, 1997). Unlike *Graphic User Interfaces (GUIs)*, shape-changing interfaces could make the abstract information and computation tangible and thus facilitate manipulation by users (Ishii e Ullmer, 1997). Another reason is that such interfaces allow for displaying dynamic content (Ishii *et al.*, 2012). For all these reasons, numerous researchers have created dynamic and actuated objects to enrich interaction experience (Kim *et al.*, 2016; Le Goc *et al.*, 2016; Wang *et al.*, 2018). However, most of the shape-changing interfaces remain quite small (handheld or tabletop) and I think there are many potentials in using them with large setups such as interactive walls. With shape-changing abilities, walls could not only combine both the advantages of tangible physical entities and adaptive information displays, but also dynamically separate space and even bear the weight of people in view of the large size. That is to say, walls could function as hidden furniture.

For instance, imagine a user going back home from work. He/She would put down his/her clothes and keys on some containers in the walls. When he/she went to work on the next morning, the wall could be actuated to bring him/her back the coat and keys, and the containers would automatically move back. As it was stated in (Aryal *et al.*, 2018), people would get satisfied when they could change the environment conditions. From this scenario, the requirement of changing the environments could be seen.

Several artists have already investigated how to create practical shape-changing wall systems (Rogers e Studio, 2010; Rozin, 2015). Nonetheless, there has been little research effort dedicated to interaction design with such vertical dynamic wall systems, in comparison with the large number of researchers who investigated gestures interaction with tabletop or vertical displays. To fill this research gap, in this project I aimed to explore the interaction for dynamic vertical reconfigurable and automated wall systems. From the study, I found that people would prefer to touch the interface if the components were accessible, while they tended to use tools or voice when the pattern was out of reach. Additionally, end-users would like to get immediate feedback. Furthermore, I provided some recommendations for interaction design.

2.2 Research Questions

The goal of this project is to understand how end-users interact with interactive walls. In particular, I am interested in investigating:

- What kind of applications end-users would want with an actuated wall?
- What types of interaction (voice user interfaces, gestural user interfaces, touch etc.) end-users would want to use to interact with an actuated wall?
- How the dynamic of the wall impact user interaction with it?

2.3 Methodology

To answer the questions from above, I used four steps:

- At first, I conducted workshops (N=9) to collect possible functions of the system from people with different backgrounds. The workshops were in the form of brainstorming.
- Then, based on the ideas got from the ideation session, I performed an elicitation study (N=20) to investigate how participants would interact with the walls to finish set tasks. The whole process was videotaped by the camera.
- After that, in order to study participants' expected feedback from the walls, a simple design session (N=6) was operated.

- Finally, I also implemented a low-fidelity prototype to investigate the possible implementation of an actuated wall system using simple fabrication methods. My implementation used 3D printing technology to build the model, Arduino to control the movement and stepper motors to move blocks.

2.4 Deliverables

Possible and promising functions of shape-changing wall systems: Holding workshops to brainstorm on the potentials of such wall systems.

Intuitive types of interaction for large-scale vertical systems: Conducting an elicitation study to see how end-users would interact with the system under certain tasks, and a user study to get the intuitive and expected feedback.

A prototype of a small-scale shape-changing wall: Making a small-scale prototype to prove the concept. The components of the mock-up could move in and out individually under the control of the control module.

2.5 Added value

An increasing body of research investigated shape-changing interfaces. However, they were mostly limited in small-scale and horizontal displays. Artists attempted to make large-scale interfaces dynamic, but few work has focused on the interaction design for such systems. This project dealt with how people would interact with dynamic wall systems and what feedback end-users would expect. It could fill the research gap that there has been little work dedicated to the interaction design for such systems. Also, based on the results of the study, designers and architects could create actuated dynamic wall systems with better interaction. In a word, this project should contribute to improving the interactive experience within future buildings.

2.6 Scope

This project focused on the interaction with shape-changing wall system, which consisted of an array of actuated blocks. The methodologies and guidelines, however, were not constrained to this specific system. They could be adapted and applied elsewhere. For example, when referring to the systems with other dynamic mechanisms, they may also be able to instruct the intuitive interaction design for such systems.

3. CHAPTER 2: BACKGROUND

The primary focus of the background was to review a series of papers which contribute to the interactive gesture sets, methodologies of interaction design, shape-changing interfaces and design for living space. The first two parts provided comparisons and interaction techniques for my project, while the latter two parts demonstrated the primary focus and offered potential ideas for future work.

3.1 Interaction Design

A majority of studies investigating the intuitive interaction with diverse interfaces and objects, especially the digital screens, have focused on the gestures. Additionally, when referring to interacting with large-scale objects, like the shape-changing walls, the proxemics worth studying. Thus, in this section, I focused on the gestures design of interactive devices and proxemics design of large screens.

3.1.1 Gesture-based interaction

To support the gesture recognition, researchers have created multiple technologies and used these technologies in implementing the prototype. Two most commonly adopted ones were the capacitive touch sensing and computer vision. For instance, DiamondTouch (Dietz e Leigh, 2001) used the former technology to support multiple users' operations. The typical system using the latter technology would be PlayAnywhere(Wilson, 2005). Thanks to the technologies, gestures could be recognized whenever they were performed on an interface or in air. In this way, the gestures could be divided into surface gestures and motion gestures. The first one was related to operating on the surface to control the content, while the second one was to move the devices.

3.1.1.1 Surface gestures

For the studies of surface gestures, Wu and Balakrishnan summarized, described and tested the multi-finger and whole hand gestures (Wu e Balakrishnan, 2003). Based on that, Jacob et al. investigated the gesture preference of tabletop surfaces (Wobbrock *et al.*, 2009). In the paper, they created a gesture set for participants to do under specific tasks. Every task functioned as referents, and the participants were expected to perform the cause. In order to better investigate intuitive gestures, people were asked about their favourite gestures. The implementation of the user study and the gesture set got were instructive. In my project, I referred to the strategy and designed the tasks with referents. The screen in this research was tangible, while in reality, people may be in the position afar from the interfaces. To explore the interaction, in that case, researchers turned to rely on associated displays. For example, Shahzad et al. developed an interactive technique (Malik *et al.*, 2005) to facilitate controlling from a distance. The technique was to set a workspace that was correlated to the system and users were supposed to operate on the touchpad to track. It provided a valuable direction for further study in using tools to interact with dynamic actuated systems like the walls. Some work aimed to add the input's degree of freedom to three. Liu et al. developed new techniques named TNT (Liu *et al.*, 2006), which supported reorientation on digital tabletop interfaces. Observational studies were implemented to gather detailed and useful techniques. Researchers observed how the participants would pass the paper around. Such observational study approach was also used in the (Epps *et al.*, 2006). Authors gathered and categorized the observed hand shapes and calculated their frequency of usage. The result was shown in the form of the table, and the form could be used as well in my study.

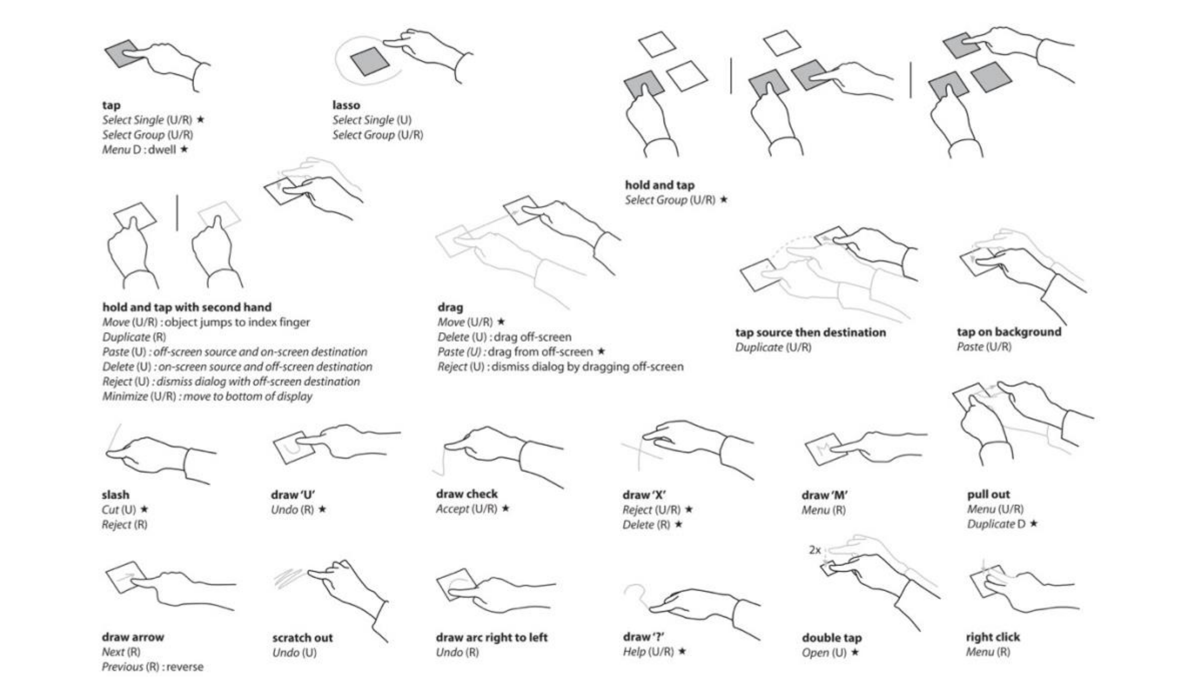


Figure 1 Part of the gesture set used in (Morris *et al.*, 2010)

The evaluation part of the gesture interaction was also crucial. An excellent example of this would be the exploration of the man-machine interaction (Nielsen *et al.*, 2003). In this study, except evaluating the human-based gestures, researchers also investigated the technology-based gestures. They created a table to record people's different gestures for the same function, whether the gestures were dynamic or static, and the frequencies of each gesture. The methodology was beneficial for the analysis of my study.

3.1.1.2 Motion gestures

The motion gestures were about moving the devices rather than body parts to achieve a specific goal. Early in 1996, Rekimoto (Rekimoto, 1996) created a tilting prototype containing a palmtop display for users to operate the menu, such as controlling the scroll-bars and selecting items. Based on that, researchers (Harrison *et al.*, 1998) developed a tilt detection interaction prototype for navigation. The testing results showed that the tilting degree was hard to control, and it led to targeting difficultly. Similar to the research on gestures of tabletop interfaces, Ruiz et al. (Ruiz *et al.*, 2011) investigated about how to enhance mobile devices user experience by moving the devices, and based on the analysis results, they developed a motion gesture set.

3.1.1.3 In-air gestures

The advanced technologies provided conditions for the recognition of in-air gestures. To find the users' preference about such gestures, Epps et al. (Epps *et al.*, 2006) displayed a set of static pictures to users and required them to perform actions on the objects. With the gestures got from the study, they summarized and categorised all the hand gestures by the hand shape. However, in the whole study, they only showed the prompt of the tasks, and it would cause confusion. Also, they did not raise a set of gestures.

3.1.2 Proxemic interaction design

Because of the large size and vertical placement, the use of space and its effects on human behaviours and interaction were studied. Large-scale vertical displays were usually placed in public spaces. The distances and space could influence people's behaviours and thus may impact interaction. In 1910, Hall came up with the idea of zones before the wall, and he named them as 'intimate', 'personal' and 'social' zones (Hall, 1910). Based on that, Nicolai (Marquardt, 2013) studied peoples' and appliance's proxemic relationships and gave instructions to interaction design. In this study, the author brought five key proxemic dimensions for interaction study, namely distance, orientation, movement, identity and location. In my project, to fulfil the interaction investigation on different occasions, distance and movement dimensions were taken into consideration. To specify the impact of the factor distance had on users, Cheung et al. (Cheung e Scott, 2013; Cheung e Scott, 2016; Ghare *et al.*, 2018) did a series of studies to define the three 'zones' in from of the wall displays: 0-1m, 1-1.5m, further than 1.5m (see Figure 2). The first zone was named as 'personal' and was the nearest zone with the system that allowed the users to touch the wall. The second one was 'subtle' zone that enabled people to interact with, while the third one, 'social' zone was studied and designed to attract passers-by. In this case, in view of the project's aim was to explore the types of interaction, the first two zones were borrowed to divide the space in front of the wall system.

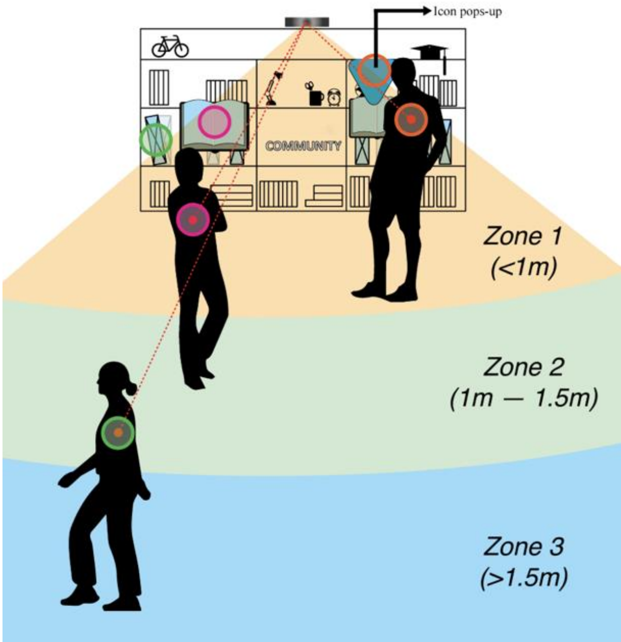


Figure 2 Distance Zone (Ghare *et al.*, 2018)

3.2 Methodology of Interaction Design

3.2.1 User-centred Design

The most frequently used design method is User-centred Design (UCD) approach. Different from other approaches which take the system as the essential element, it is a design approach focusing on the human side. It means that the design should have a high quality of user experience. Furthermore, it included the Iterative Design approach whose purpose is to refine the design process and thus achieve an agile development. When conducting a design project, it suggested that designers should follow a spiral model, which means iterating in three stages: evaluation, design and implementation. To lower the developing cost of the prototype and improve the efficiency, I used this approach in my project when I was designing the prototype. Based on the results got from ideation workshops and the elicitation study, I firstly used a servo motor to drive the wood cube to move. When it came to a problem, I turned to use stepping motors. Only when the structure worked, I installed the component and then developed more.

3.2.2 Elicitation Studies

A number of interaction designs have directly involved users in the design process. The method is most evident in participatory design (Schuler e Namioka, 1993). Then came the elicitation study methodology, which employed users to help with the design. The user elicitation study methodology was first presented as a method to define intuitive and easy using gestures in (Wobbrock *et al.*, 2005; Wobbrock *et al.*, 2009). Elicitation studies are popular among the researchers for the reason that they provide researchers with valuable information about how people think and feel about the behaviour (Downs e Hausenblas, 2005). A study which elicited input from users was conducted by Liu et al. (Liu *et al.*, 2006). They observed how users passed sheets of paper on the table and then designed the TNT gesture to emulate this behaviour. Another study related to the elicitation studies implementing was conducted by Morris et al. (Wobbrock *et al.*, 2009). It offered an example for exploring users' interactive gestures with a specific surface. The study process could be summarised in the following way. Firstly, researchers showed participants an example to give them a brief instruction on how to manipulate the interface following the commands. Then, let them imitate the behaviour to strengthen the impression. After that, participants were presented several interaction gestures to rate. In this way, researchers could analyse what is the best for that command. However, in this study case, all the interaction gestures have to be stated in the beginning. It is not so applicable in my situation because I aim to explore intuitive methods of interaction rather than compare some of them. Therefore, to involve the end-users into the exploration of interaction design, I assigned the tasks for users to accomplish by interacting with the system.

In summary, I used the elicitation study methodology in the project to find out how to interact with actuated vertical surfaces.

3.3 Shape-changing Interfaces

Shape-changing interfaces have been a vital research topic of Human Computer Interaction. As stated in (Suh *et al.*, 2017), such interfaces could absorb the simplicity of physical objects and combine the simplicity with the expressiveness of actuated substances.

3.3.1 Tangible actuated surfaces

As Hiroshi et al. (Ishii *et al.*, 2012) claimed, tangible interfaces enable to express digital information by a physical embodiment directly. Tangible actuated interfaces is a promising research focus in delivering dynamic information. A typical case in point is inForm (Follmer *et al.*, 2013), a horizontally actuated interface introduced by Follmer et al. (see Figure 3). Every component of inFORM was simply a cuboid and able to move up and down individually. In this way, users could manipulate objects on the interface. Also, with the help of the projection, the interface was able to express precise information. It created a pixel real-time 2.5D shape actuation and thanks to its variability, it inspired loads of research on shape-changing interfaces.

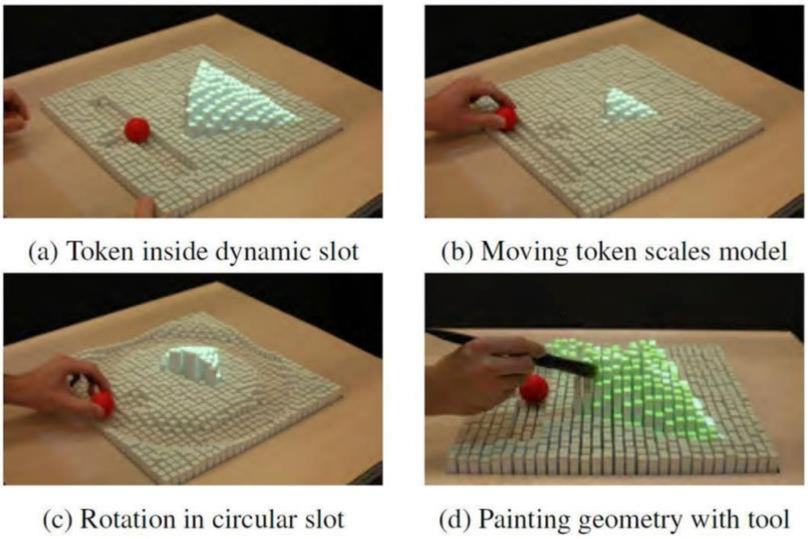


Figure 3 The manipulation of the 3D model in inform (Follmer et al., 2013)

Another classic example is Zooids (Le Goc *et al.*, 2016), developed by Le Goc et al. The platform consisted of a collection of wheeled microrobots, and all these microrobots could move dynamically under control. Users could change one microrobot's position, and because of the magnetic force, other microrobots would move accordingly. These physical pixels, as a whole, would deliver information by their placements. Meanwhile, the data became tangible and could be interacted with intuitively. Another example is (Taher *et al.*, 2015), which aimed at exploring the mean to analysis data by a shape-changing system. Researchers in this project constructed a physical bar chart by an array of LED-lit rods (see Figure 4). The numerical values were represented by the heights of rods. In this case, the dynamic data could be touched and sensed directly. In addition, the researchers investigated the interaction with the device by testing people's reactions to the set tasks. The authors found from the study that users receive a sense of definition when operating physical interfaces.

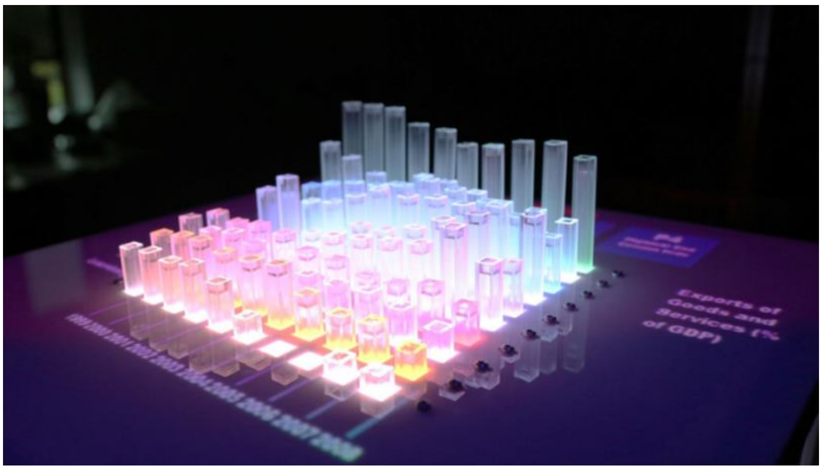


Figure 4 EMERGE developed by Taher et al.

The former interfaces were all solid ones, while the different states of objects might also have an influence on the interaction. An impressive instance that has to mentioned is AquaTop Display(Matoba *et al.*, 2013). Unlike the solid objects, this project was about liquid. The display chose liquid as a projection medium and explored the interaction with such different interfaces. For the reason that the liquid interface had depth, the freedom of interaction was largely increased because participants were able to interact under the surface. To record this variable, a depth camera was added into the system. Moreover, speakers were soaked into the liquid to provide tactile and visual feedback.

3.3.2 Shape-changing vertical surfaces

There has been comparatively little research effort dedicated to the shape-changing ones. Most of the actuated vertical displays were limited in the artistic field. For example, in Designed for ILIDE (Italian Light Design) and Exhibited at the Milan Design Week in 2010, Francesca Rogers and Daniele Gualeni Design Studio displayed Light-Form(Rogers e Studio, 2010), which was a system consisting of an array of lights on the wall and could be turned off by covering wood boards over the lights. Though the interaction was limited, the system engaged users and provided a sense of entertainment. The main advantage of the system was the intuitive interaction and instant feedback. Similar to this project, in Retail Design Expo (RDE) in 2015, a design work named Engaging Space(Pow, 2015) created by Dalziel & Pow was shown. This artwork aimed to use interactive walls to perform storytelling. All the elements on the wall could be interacted with by pressing and touching. Nonetheless, such design was more installation art than technical interaction design.

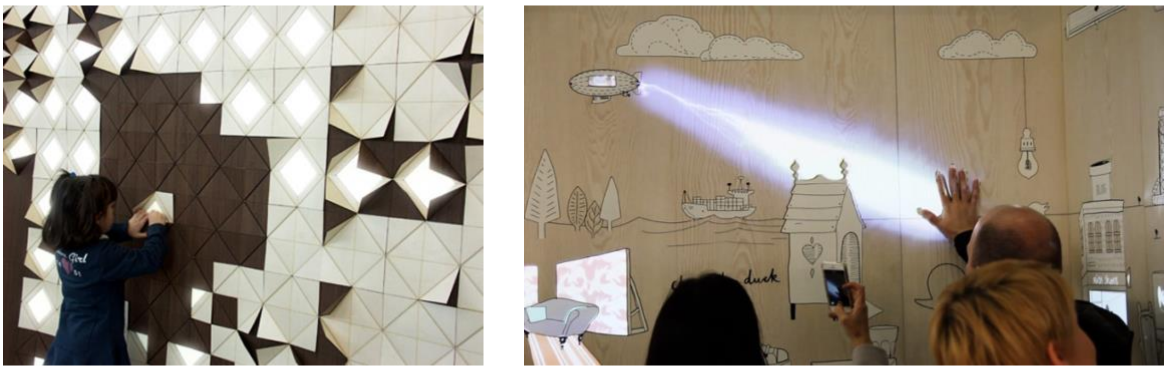


Figure 5 The left one is Light-Form(Rogers e Studio, 2010); The right one is Engaging Space(Pow, 2015)

In 2012, architects in MIT School of Architect and Planning created HypoSurface (Mark *et al.*), which was made of thousands of tringle faces (see Figure 6). In this way, users could push the surface to interact. The installation functioned more as a tool for entertainment purpose rather than to accomplish specific tasks such as being a piece of furniture. However, in the future, interaction with such a shape-changing mechanism deserves to be investigating.

Figure 6 HypoSurface, a dynamic interactive surface (J e Ger, 2017)

All these studies mentioned were mainly for artistic purpose. Though some actuated tangible design research allows for input and output in the vertical direction as previous examples, the controlling interfaces are mostly horizontal, such as (Malik *et al.*, 2005). As can be seen, vertical interfaces with direct interaction have been overlooked. Furthermore, among the research, most of the projects were limited in the design for group work. It may result from the fact that larger surfaces are relatively suitable for multi-users' operation compared with smaller ones. For instance, early in 2001, Guimbretière (Fran *et al.*, 2001) intended to design a wall-size display with fluid interaction. The goals of the project were to achieve high resolution of displays, clean the screen and support fluid interaction. The final system allowed users to manipulate the information on the screen, other than just to watch the static information on a whiteboard. It inspired research interests in designing for tangible vertical interfaces. In 2004, Rogers et al. (Rogers e Lindley, 2004) compared the different impacts of vertical and horizontal displays on group working. In addition, from the prior study, the researchers got the comments that standing in front of the vertical systems for a long time could result in social awkward and additional task difficulty because the process was unnatural. Given the fact that, to avoid this problem, in my study, I made the tasks short and in random order. Moreover, they came to the conclusion that horizontal displays would facilitate cooperation for multi-users. Based on that, Jens et al. designed furniture(Gr *et al.*, 2017) for meetings which was able to shift the shape between horizontal and vertical. The furniture was consisted of two boards and could rotate around an axis. Nonetheless, the interface was still designed for meetings and methods for interaction were limited. Further, Risa and Kaori proposed CrosSI (Otsuki e Fujinami, 2018), a multi-surface information display system. This design connected horizontal and vertical surfaces smoothly to support a higher quality view of information. However, all of them lack further research in adding actuation into vertical interfaces to diminish the limitation of static shape.

Besides all the work stated above, a most relevant and vital inspiration of this work was the Hyper-Matrix (Jônpasang, 2012), which was an art installation shown in 2012 Yeosu EXPO Exhibition (see Figure 7). In this artwork, Hyundai Motor Group enabled the interfaces to display different patterns based on the movements of cubes, while the audience sat in front and watched silently. The project was gorgeous, but it stayed at the function of delivering information and omitted people's interaction experience. Making full use of the system's physical intuitiveness and allowing it to receive and process inputs from users are what I tend to accomplish in this master project.

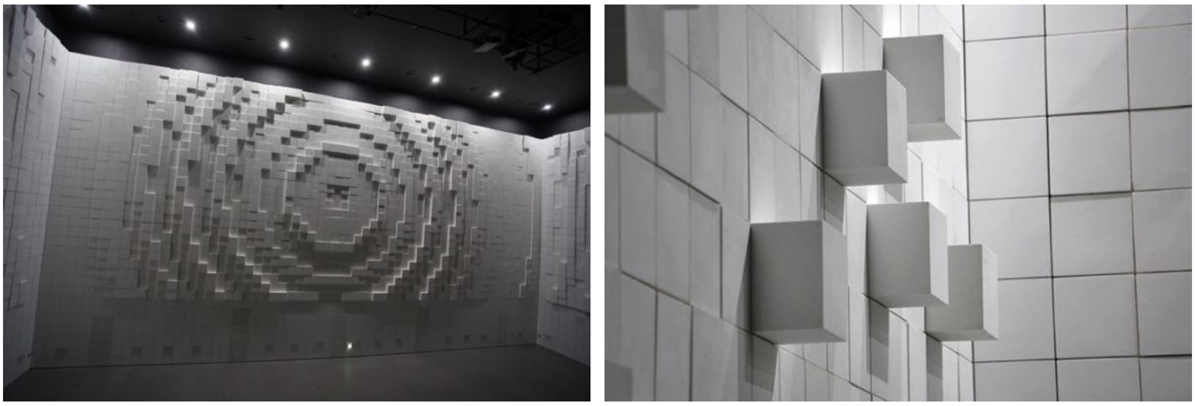


Figure 7 Hyper-Matrix Cube Wall (Jônpasang, 2012)

3.3.3 Pin-based shape-changing interfaces

One main focus of the research of the shape-changing surfaces is investigating pin-based systems' applications. For example, based on inFORM (Follmer *et al.*, 2013), which has been mentioned before, the MIT media lab proposed Materiable (Nakagaki *et al.*, 2016) to represent material properties. It provides a template to discover other kinds of information shape-changing interfaces could deliver. As demonstrated in this work, one primary ability of these displays is to move and manipulate objects. Seeing that, Schoessler et al. (Schoessler *et al.*, 2015) introduced an innovative method to operate objects based on pin-based interfaces. In order to extend the possible shapes, they made blocks magnetic, and they could thus stick to each other. To control the blocks to form the expected shape, they were put on a similar interface as inFORM. Thus, with the rods popping out and moving in, the input and output of the display were mainly enriched by such kinetic actuation. However, it did not allow for providing feedback about the actuation. That means there would be no actuation results, and it should result in unnatural interaction. Another example was TilePoP (Shan-Yuan *et al.*, 2019). The floor was made of airbags, and thus the interface was pneumatic. In this way, when being inflated, the tiles could form a similar shape with the vision in VR. It provided another solution to pop out pins and another possible application that such interfaces could do.

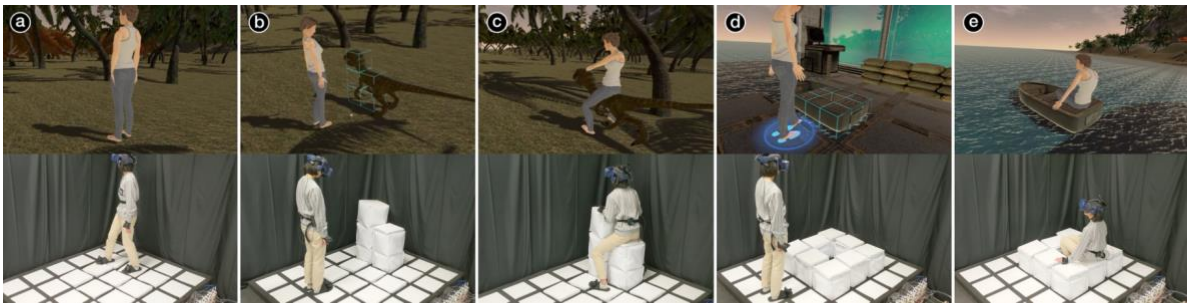


Figure 8 TilePoP (Shan-Yuan *et al.*, 2019)

Things are different when applied to mobile devices to enhance mobile phones' user experience because mobile phones have to receive input from users. In this case, Sungjune et al. (Jang *et al.*, 2016) proposed a novel type of haptic mobile device with a pin edge to enhance the experience. Each taxel of the edge had a touch sensor that acted as an input element. Nonetheless, because of the size, the interactive method was kind of limited, and the requirement of sensitivity was much higher. Another example is Tilt Displays (Alexander *et al.*, 2012) developed by Jason et al., which provided interaction with multi-axis tilting and vertical actuation. Since every component had its axis and display, it could show information in different angles theoretically. However, because the primary implement of it was based on small-scale usage scenarios, the effects were hard to predict when applied in the large-scale scenario. Thus, to create a large-scale, interactive and efficient system, the component size should be reasonable.

As can be seen, these attempts were all dealing with horizontal or small-scale vertical interfaces which would react differently on users' input. There should be research going beyond such shape displaying.

3.4 Design for the living space

In recent years, the design for people's living space usually concerns the design for smart homes, which uses digital intelligence to control appliance, such as (Suryadevara *et al.*, 2012). These home automation systems generally consist of three components, namely a control module, a protocol of transmission, and devices and applications (Karimi e Krit, 2018). In other words, controllers, sensors and devices are essential elements to consider during the design process. Hence, a number of efforts are made in developing faster controllers and applying multiple sensors to collect immediate information about the living space. Also, all kinds of appliances and devices designing innovative displays. Besides, with these data, researchers could also make the environment adaptive in order to facilitate the living experience.

3.4.1 Controllers Design

The fact that the processing speed of controllers is becoming faster could be well explained by the development history of Arduino and Raspberry Pi. Arduino is a lightweight micro-controller which was created in 2003. It is an open-source hardware and developing at such a high speed as to become a perfect choice to control LED lights, servos and other sensors. On the other hand, Raspberry Pi is a small, fully functioned computer, which is suitable for complicated manipulations such as image processing. These two control modules are implemented based on different usage scenarios.

3.4.2 Sensor Applications

To track the real-time state of rooms, multiple sensors are essential to obtain this information. For instance, the design (Raja e Reddy, 2017) used light sensors to sense and thus controlled the luminance level of the home. Unlike this example, some research focused on sensing and tracking users' activities, including their positions and gestures. A good example would be GravitySpace (Bränzel *et al.*, 2013) developed by Bränzel et al. It applied gravity-sensitive floors to detect multiple users' position and poses. Similarly, Wall++ (Zhang *et al.*, 2018), which implemented large electrodes with conductive paint to make existing walls smart infrastructures. It could track users' touch, gestures and also estimate body pose. Afterwards, appliances will react according to these signals. Nonetheless, the installation process is complex, and the cost of implementing this to all walls in homes is high. Another case in point is (Kim *et al.*, 2013). Researchers implemented Radio-Frequency Identification(RFID) technology to identify the elderly's positions and thus to indirectly protect their safety.

3.4.3 Display Design

As to enhance the interaction experience, researchers redesigned the display interfaces and other forms of feedback. For instance, ExtVision (Kimura e Rekimoto, 2018), proposed by Naoki and Jun, calculated and projected context-images to the periphery of the devices like TV screens to augment visual experiences. However, despite that the visual experiences could be improved, the feedback is still two-dimension, and what is more, users could hardly interact with the device. Walls, as I stated before, serve as a vital factor in living space. Thus, enhancing interaction between walls could largely improve users' living experience. A good example of that is the electronically augmented wallpaper developed by Leah et al. (Buechley *et al.*, 2010), which could be used for a multitude of functional applications such as lighting and environmental sensing. Based on that, Sara Nabil et al. did research on Organic User Interface design for interactive interior spaces and explored the design space of interior action (Nabil *et al.*, 2017). Another direction of delivering feedback is using head-mounted display.

It could add 3D models to the real scenes, thus enables users to design by themselves. A case in point is (Lee *et al.*, 2016), where users were allowed to personalize furniture with the help of HMD.

3.4.4 Adaptive Environment

As Coyne stated in (Coyne, 2015), the architecture has great potential in enhancing the interaction, including its natural support for play. Adaptive environments enhance this feature. Based on that, a theory about dynamic architecture action-reaction feedback loop was introduced by Schnädelbach (Schn e Delbach, 2016). He explained the input of people and the feedback from the architecture. Additionally, Aryal et al. (Aryal *et al.*, 2018) claimed that being able to change the environment around them would increase users' productivity and benefit their health. An interesting study about the adaptive environment is ExoPranayama (Moran *et al.*, 2016). Researchers in the project developed an actuated system moving with people's breathe in the yoga practice. The system was made by an aluminium spine and jersey fabric. By collecting and processing the physiological data from users, the position of the spine was changed by two servomotors. To better help with the interaction design between human and architecture, Schnädelbach et al. (Schn *et al.*, 2019) conducted three workshops to investigate how to use personal data into adaptive architecture. The outcome included the design space to facilitate such design.

In summary, these living space designs are limited to giving feedback using existing appliances or two-dimension display interfaces. Meanwhile, most of them cost a lot to add such value to current homes. Thus, I am to explore the actuated interactive wall systems to enhance the living experience.

3.5 Summary

Although all these designs provide ideas and implementation experience for dynamic spaces, the research on the assessment of interaction approaches seems to be overlooked, especially in the field of vertical three-dimensional interfaces. My project aims to bridge the gap by exploring people's interaction with vertical shape-changing walls and based on that, creating a low-fidelity prototype of a dynamic system.

4. CHAPTER 3: APPLICATIONS

I first conducted three workshops to understand the possible applications of a large-scale shape-changing wall system, i.e. what could be the usage of such systems. Interacting with a system is about sending and receiving information to and from the system. Because the transferred information varies according to the system functions, functions need to be defined before exploring the interaction design. Thus, I conducted ideation workshops to investigate the extended functions of shape-changing wall systems in pre-set usage scenarios. Three usage scenarios were set to be at home, in the workspace or the school, and public space. I chose these in consideration of that they were the most commonly used scenarios. Volunteers of diverse backgrounds were recruited to brainstorm about the possible functions. As a whole, the workshop investigated the diverse range of appliances that shape-changing wall systems could have and provided bases for the user study.

4.1 Participants and Apparatus

A total of 9 participants (23.4 mean age, 1.01 std dev, 6 females) were recruited in the study. Participants were students in the local universities and from a range of backgrounds: 3 in computer science, 3 in architecture, 3 in design. All of them had a minimum of 5 years of study in their disciplines. One designer mainly focused on speculative design, while the other two had extensive experience in industrial design. Among these three architects, two of them focused on building engineering physics, and the other one had formal training in architecture design. To compare the different ideas of people from various backgrounds, people were grouped by the educational background and participated in the workshop separately. A set of brainstorming cards were designed to facilitate the design thinking process. There were seven aspects printed on the cards, including five Ws (Where, When, What, Who, Why) and two essential attributes which were determined through the discussion with two other architects. These dimensions were places, situations, residents and visitors, activities, measurement, materials and environment, and they could facilitate ideas generation.

Figure 9 Brainstorming Cards

4.2 Procedure

Introduction: The workshop began with a 10-min introduction to demonstrate the purpose of the study. Information sheets and consent forms were delivered for permission of further study on the data. Also, a PowerPoint presentation was displayed during the whole process to facilitate the idea of forming and the instructions demonstration.

Warming up: In this session, two questions were raised to facilitate participants' thinking. They are: 1. What functions could you recall of a wall? 2. What functions would you consider appropriate to add to a wall? For inspiration, pictures of walls were displayed on the screen, and sticky notes of different colours were provided. Also, every participant was given a set of brainstorming cards for the entire process. For each question, participants were required to write their ideas on the notes and stick on the whiteboard within the limited ten minutes. After that, they shared their ideas in the group.

Brainstorming: At the beginning of the session, sets of Lego© bricks were provided on the table for every participant to fiddle around. They were aimed at helping participants to form ideas with manipulating these physical pieces. Furthermore, an introduction video was displayed on the screen to better demonstrate the idea of the pixel-based shape-changing wall system. Then the pre-set scenario was assigned to the group, and participants were expected to design the basic functions the shape-changing wall system could have in the scenario. The three scenarios were 1. in a smart home, 2. in a smart building of university campuses or workspaces, 3. in the public space like a train station and a shopping mall. These three scenarios were assigned to computer science, architecture and design students separately. Volunteers would write down their ideas on the sticky notes as well.

Group Discussion: In this session, participants were asked to come up with four top ideas of the functions. An ideation record table was provided to help organize the ideas. Participants shared their sticky notes in the group in turn and stuck them on the whiteboard. Similar ideas were merged, and the stickers were pasted together. Then every group chose four best functions for the scene and filled in the ideation record table.

4.3 Results

I present the possible applications of shape-changing wall systems derived from the ideas raised by the participants in the workshop (see Figure 10). In the workshops, every group brought up four general applications. I merged similar applications and redesigned the categories. Then, I reorganized ideas into different categories (see Figure 11).

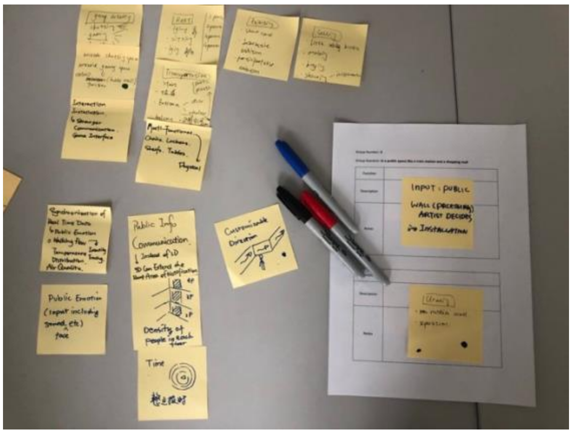


Figure 10 Part of Brainstorming Notes

Scenario 1: in a smart home

Items Delivery: Alice uses the wall to deliver items. Since the blocks could move individually, when popping out in order, they could move items horizontally. She commands with hand gestures to get certain things from a distance.

Smart Screen: Bob combines the wall with electronic screens. Every block has a small screen fixed on the one face. In this way, the size of the screen could be adjusted. Also, he states that the angle of screens could be changed as well.

Smart Furniture: Carmen uses the wall as furniture which could be formed and hidden at will. Blocks moving out could serve as chairs, tables or stairs. Alice thinks the shape-changing walls could make phones adhered so that phones could be used while charging vertically. Also, her wall could store items. She instructs the wall to form a container of the expected size to store things.

Scenario 2: in a smart building of universities campus or workspace

Change Interior Environments: David uses the shape-changing wall to change interior environments like the light environment, air circulation and the structure. From an architecture design perspective, he thinks that smart buildings should meet the needs. As an illustration, he shifts the shape to change the amount of light transmission according to the weather and time. Besides, he uses the wall as air inlets to guide the wind directions. Apart from these, he considers using the system to provide seats, storage space or even turn a lecture hall with steps to a basketball court.

Change Interior Transportation: Eva uses the wall to help with vertical and horizontal traffic. She forms stairs for users to get to the upper floor. As for the horizontal traffic, she uses the wall to change the traffic flow.

Space Experience: Frank uses the wall as a tool to enhance the space experience. His blocks in the wall could move with music or provide a specific message. Despite these, his wall could provide directions for visually impaired people or other people in darkness.

Information Delivery: David uses the wall as a carrier of all kinds of information. In school buildings and offices, his wall could display real-time data such as weather information and time. When the components are tiny, his wall could provide braille for people with visual issues.

Scenario 3: in a public space like a train station and a shopping mall

Public Art Installation: George uses the wall as an art installation in public space. His wall could receive people's behaviours as input, and such behaviours could be personal or group's. The shape would change according to the input. The processing methods are open to artists. For example, the blocks in the area which people's shadow covers would pop out. His wall could also, in some way, indicate the movement and gathering of a crowd.

Recycling Wall: Harry uses the wall as an approach to educating garbage classification. His wall provides a specific place for garbage, and it could recognize the type of rubbish. Because the wall could construct different paths, with forming a corresponding path, the garbage would be sorted in a visible way.

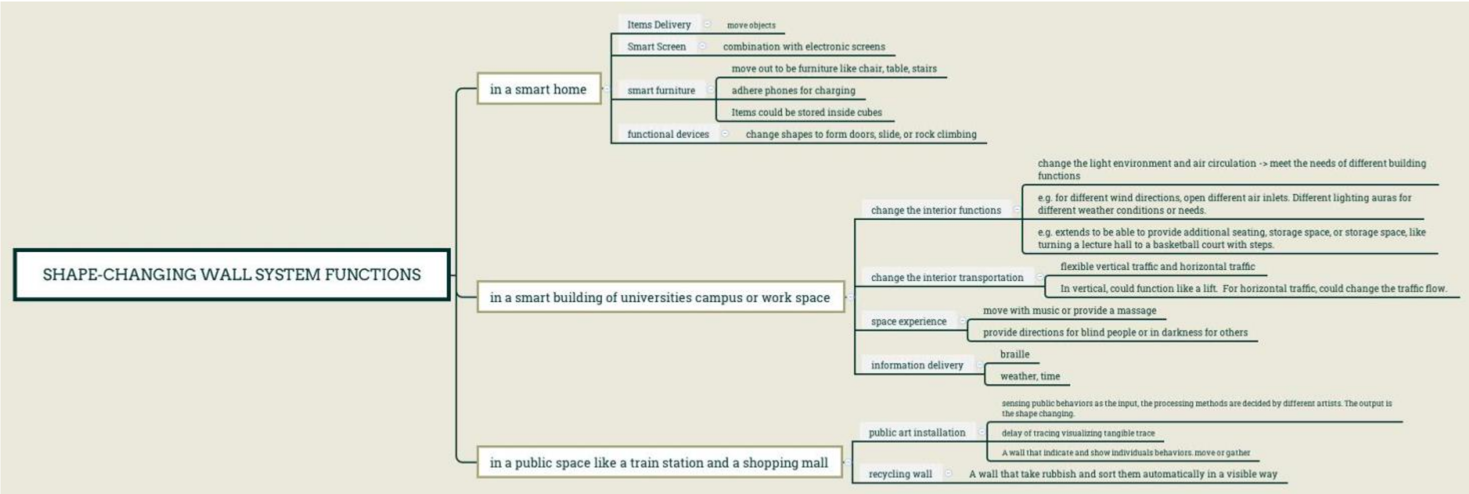


Figure 11 Ideation Results

4.4 Design Space

In this section, I present a design space for the shape-changing wall system. It was extracted and summarized from the analysis of ideation outcomes and the ideas got from related work. Also, it was referred to idea themes in (Sturdee *et al.*, 2015). The themes were collected through a brainstorming exercise on shape-changing applications.

- **Augmented Living**: The shape-changing wall system could improve general life quality by contributing to smart furniture and interior traffic. With users' instructions as input, the cubes in the system could move out to be furniture like a chair and stairs. When the cubes are made hollow, they could also function like a dynamic closet or a cabinet. Moreover, the cubes could form different vertical paths so the system could be used as a smart bin with the intelligent garbage classification. As for the interior traffic, the wall could benefit both ordinary people and disabled people. For example, the system could provide tangible navigation for people in darkness and blind people. Furthermore, with blocks sticking out one by one, it is possible for the system to carry people to a particular spot. A case in point is inFORM(Follmer *et al.*, 2013) which was developed by Follmer et al. It was a horizontal system which enabled the object movements.
- **Architecture**: Shape-changing walls support changes of building forms and interior alterations. The scale, light environment and air circulation could be changed by shape changing, and thus, it could meet the needs of different functions. A good example would be the wall system could open different air inlets for different wind directions. In addition, the system could hide essential infrastructures like doors to make the interior space clear.

- **Communication**: The wall system helps with information communication. In the project Tilt Displays(Alexander *et al.*, 2012), the screen allows for displaying to different angles. Every block in the system, when popping out, has five faces that could convey information. The information includes real-time information like weathers and other information like the properties of objects. For instance, Nakagaki et al. proposed to represent material properties with shape-changing surfaces(Nakagaki *et al.*, 2016). Also, when the size of every block is small enough, the system could form braille. For long-distance communication, the system could be a tangible reminder, and the message could be three-dimensional.
- **Entertainment**: The walls could function like entertainment devices. Cubes in the system are dynamic, which means the positions of moving cubes, the time when the cube moves and the number of moving cubes could create rhythm. For example, the cubes could move with music or according to people's gestures.
- **Aesthetics**: Since the walls themselves could serve as a decoration, the shape-changing wall system could act as a dynamic art installation. One artistic work about shape-changing wall is PomPom Mirror, which is made by Daniel Rozin (Rozin, 2015). It created a dark shadow of users with fur pom poms. The cubes could achieve the same effects. Moreover, in public space, when every cube represents one person, the system could demonstrate the activities of a crowd of people.

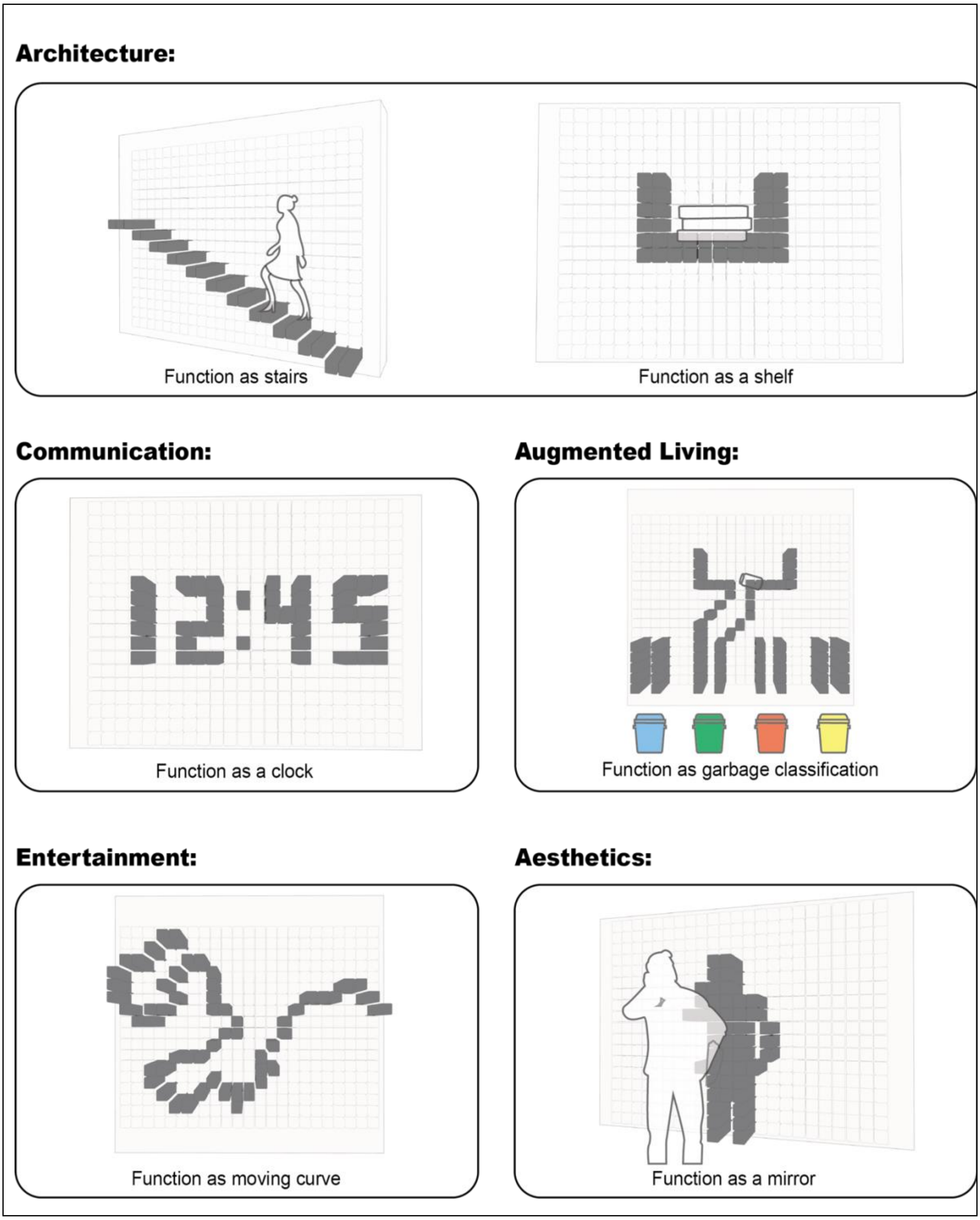


Figure 12 Five applications of shape-changing wall system

The applications which demand high creativity and are not unique to the shape-changing walls were not suitable for the general interaction study. Similarly, those applications which unable to change the output based on input from people were not taken into considerations. Therefore, I selected the forming furniture as the main application in the following elicitation study.

5. CHAPTER 4: ELICITATION STUDY

I then conducted an elicitation study to understand how end-users would interact with such a system. My goal was to understand the natural interaction between human and large-scale vertical shape-changing systems, especially wall systems. The study was aimed at gathering and analysing user inputs. Unlike parallel interfaces, vertical surfaces allow users to interact within a larger space. That is to say, the difference in the distance between the surface and the user could result in various ways of interaction. Moreover, the size of the components could also have effects. Because of this, the study took measurements into consideration. For every task, the users were required to interact with blocks of different sizes within two different zones. The think-aloud protocol was applied in the study, and the whole process was videotaped by a professional camera.

5.1 Participants

Twenty participants volunteered for the study (25.1 mean age, 3.56 std dev, 10 females, recruited from the local university). They were from diverse backgrounds: 8 in Computer Science, 3 in Management, 2 in Marketing, 2 in Human Computer Science, 2 in Electronic Engineering, 1 in Japanese, 1 in Nutrition and 1 in Biology. Nineteen of them were right-handed. None of them has visual or hearing impairment.

5.2 Apparatus

Because the study was aimed to explore, rather than implementing a large high-fidelity mock-up, the study was conducted with a projector, and the image projected measuring 1524 × 1524 mm. It was designed in order to mimic the real wall and make the tasks more realistic. Space before the screen was divided into two zones according to the concept of proxemics zones, which was stated and adopted in(Mojgan *et al.*, 2018). According to work, the distances between the user and the wall were divided into three zones: 0 - 1m, 1 - 1.5m and further than 1.5m respectively. Because the third zone was similar to “social” spaces in the work of Hall(Hall, 1910) and it was intended to attract people's attention. In this case, considering that the purpose of the study was concerned about interaction, I chose the first two zones in the study.

The instructions of tasks were firstly designed in the form of short videos (see Figure 13). Videos included the original status, and designed feedback of the system and the transformation was made by Unity, which was chosen to fully mimic the moving effects of cubes. The audio of every video was recorded explanations of the task. For example, for the operations to form a pattern, a recorded speech said, "Now please try to form the pattern as shown on the screen in zone 1 and then zone 2". However, in the pilot testing study, the movement of the cubes would influence participants' choice to interact. For example, in seeing the cubes were moving out together rather than separately, participants would more likely to use pull gestures. In this case, only the pictures of the original status and the expected pattern were shown to the participants. In order to better mimic reality, a real wall picture was chosen to be the background.

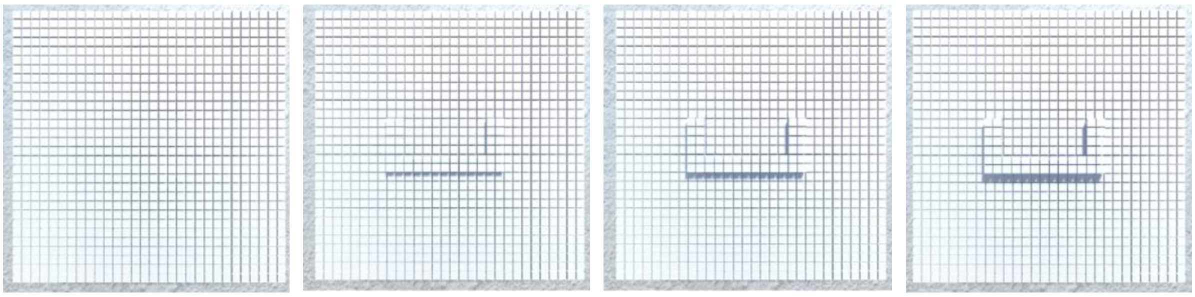
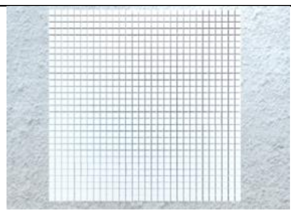
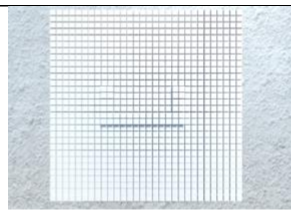


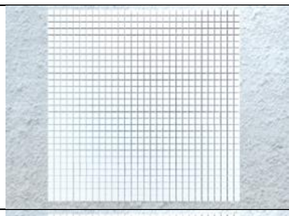
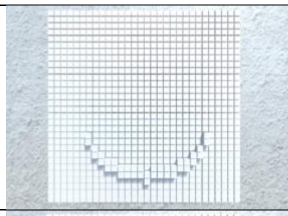
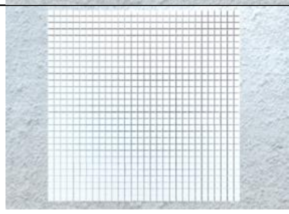
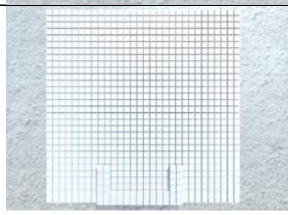
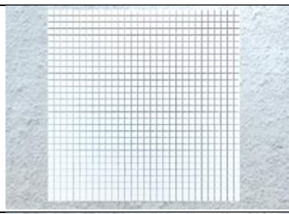
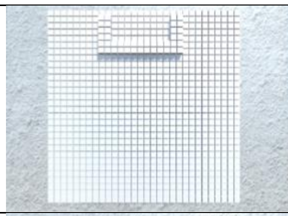
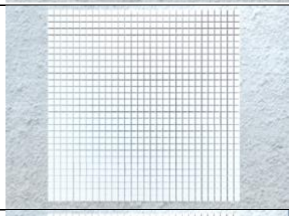
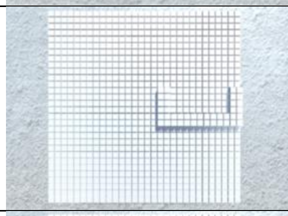
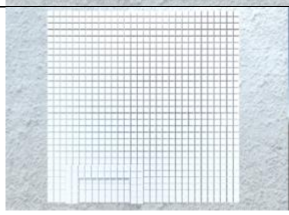
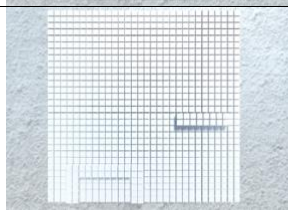
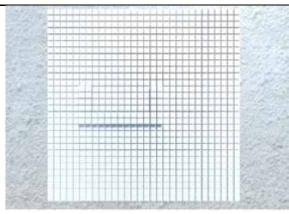
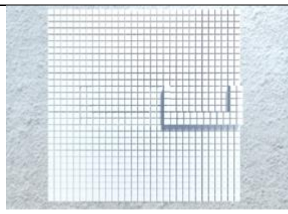
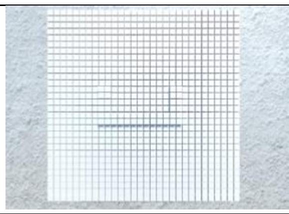
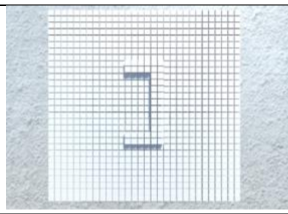
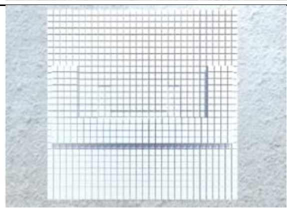
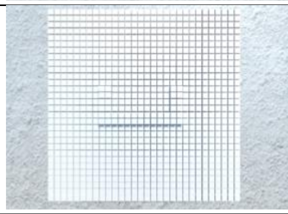
Figure 13 Screenshots of the sample video

To assure the tasks assigned to volunteers were randomised, pictures were shuffled before displaying. Then the pictures were presented continuously, and thus, participants were asked to interact with the system without being disturbed. The whole study was videotaped with a GoPro camera, which recorded both the audio and video information of the activities of participants from the backside.

5.3 Tasks

Based on the ideas got from the ideation workshop, the general function with user interaction input was selected to design the tasks, which was: serving as furniture. Furniture usually has regular shapes, and thus, the patterns in the tasks mostly consisted of straight lines. To investigate how end-users would do to form customized complicated patterns, an extra task was set to require users to form a curve. The main feedback of the wall system could be summarized as: 1. form a pre-set pattern in a certain place of the wall; 2. transform the pattern including move, rotate, reflect, scale and reverse; 3. remove the whole or part of the pattern. Thus, totally 13 tasks were set for user input study(see Table 1). Among them, the task that forming a pattern in the centre of the system from the original status served as a training to demonstrate the operations.

Operations		Tasks	Original Pattern	Expected Pattern
Form	Centre	Sample: Pop out a set pattern		

		Pop out two irregular shapes (one curve)		
	Lower Place	Form a pattern in the lower place		
	Upper Place	Form a pattern in the upper place		
	Side	Form a pattern on the side		
	Add	Add to the current pattern		
Transform	Move	Move the pattern to a specific place		
	Rotate	Rotate the pattern for a pre-set degree		
	Scale	Scale the pattern		

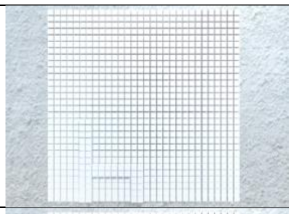
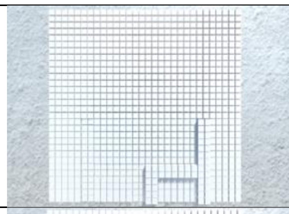
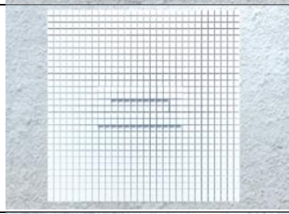
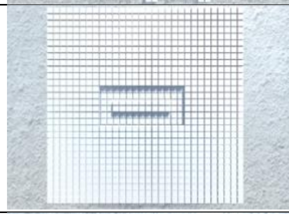
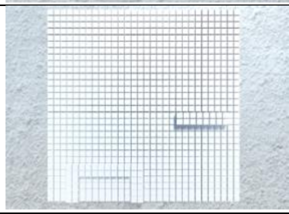
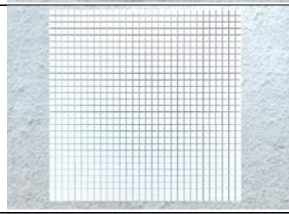
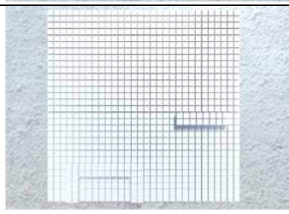
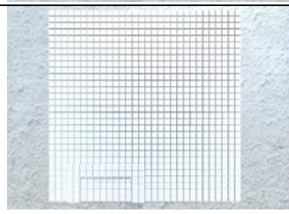
	Reflect	Reflect the pattern		
	Reverse	Reverse the pattern		
Remove	All	Remove all of the pattern		
	Part of	Remove part of the pattern		

Table 1 Tasks of the user study (take 30×30 pins as an example)

Meanwhile, two sizes of cubes were designed to form the system in order to investigate the effects that the size could have on interaction types. One had 120 × 120 pins of 12.7 × 12.7 mm to allow for the UI elements(Follmer *et al.*, 2013). Pins of another system were 50.8 × 50.8 mm, which was the similar size with Hyper-Matrix Cube Wall. Thus, every task was repeated 2 × 2 = 4 times.

5.4 Implementation

In this section, I would describe the implementation of the videos. Though in the formal tests, only pictures of videos were displayed, the training session used the complete video to demonstrate the movement and mechanism. First of all, to mimic reality, a wall picture was chosen to be the background image. Because Instead of using a canvas to create a 2D interface, I created a quad (3D GameObject) in the scene to hold the image. Then, I wrote a C# script named *CreateCubes* to form the cube arrays and control the movement. In the script, cube arrays of the specific sizes were instantiated by the function *Instantiate*. I used the array structure to store all the game objects so that I could locate certain objects more efficiently. All the tasks could be summarized into two steps: 1. Return the popped blocks; 2. Pop out blocks. Additionally, the defaulted blocks were static during the process. Thus, two groups of blocks should be marked. One is those who were out in the first place, and the other one is those who were going to pop out. I calculated the functions of lines or curves to locate the targeted components and stored them into the former two groups.

With labels on all the blocks, in *Start()* function, the original pattern was formed, while the movement was designed and operated in *Update()* function. To guarantee a smooth movement, I created a variable named *timer* to control the delay and the duration of movement, and the popping actions were achieved by the *.transform.Translate()* function.

5.5 Procedure

Session1: Interact A 5-min introduction about the basic operations was given in the beginning, and all the participants were encouraged to use whatever methods to engage with the system. Then, a training section was conducted to familiarize them with the operation. Participants were shown a video (a container was forming in the centre of the system) to be familiarized with the mechanism, and then were asked to perform whatever they thought would get that referent (e.g. framing the outline with the right index finger and then dragging the shape out with both hands). Next, randomly-ordered tasks were assigned to the participates. For each task, different from the training section, participants were shown two pictures (the original pattern and the effect of the interaction) and required to independently interact with the system to get the proposed feedback (expected patterns shown in Table 1) while thinking aloud. The possible interaction included but not limited to different gestures, body postures, voice command and tool usage. With 20 volunteers and 13 tasks including commands and feedback, a total of 20 × 13 × 4 = 1040 communication methods were created. Of these, four were discarded because of participant confusion and abandonment.

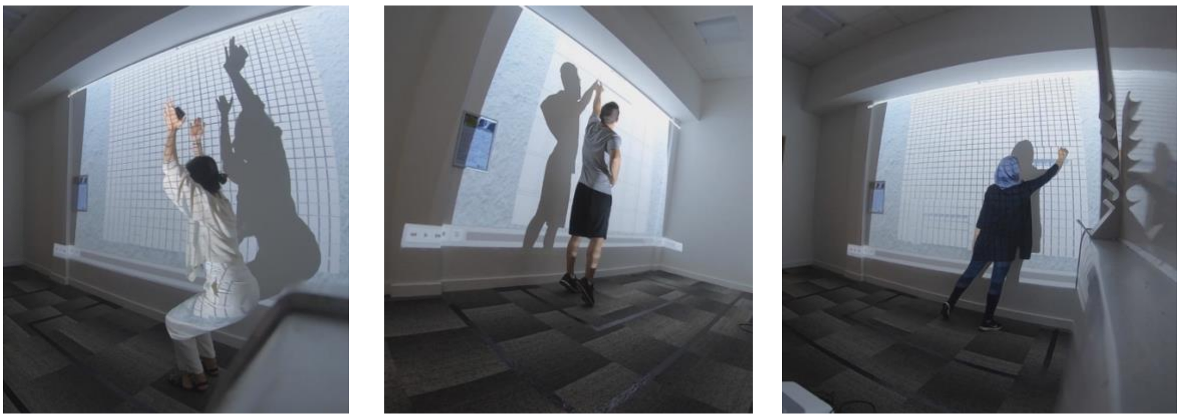


Figure 14 Performance of Participants

Session2: Post-Interview To fully understand the reason why participants chose particular methods of interaction, I conducted a post-interview. In view of their most frequently used type of interaction, three questions were asked: **Q1** What is the main difference between the interaction in two zones? **Q2** What is the main difference between the interaction with cubes of two sizes? **Q3** What are the reasons that you choose that type of interaction? **Q4** Have you noticed any difficulty or problems that may occur when interacting with the system?

5.6 Results

As stated before, there were totally 13 tasks, and each task was conducted four times for two zones and two different sized cubes. Each participant did what they considered proper to cause the effects. Totally, 1036 reactions were collected. All these reactions were categorized into three general types: "gestures", "voice command", and "tools" (see Table 2). The gestures were categorized based on the main moving part.

<table>
<tr><td rowspan="11">Gestures</td><td rowspan="3">Upper-limb gestures</td><td>Hand(s)</td></tr>
<tr><td>Finger(s)</td></tr>
<tr><td>Arm(s)</td></tr>
<tr><td rowspan="2">Lower-limb gestures</td><td>Foot</td></tr>
<tr><td>Leg(s)</td></tr>
<tr><td rowspan="6">Body gestures</td><td>Move</td></tr>
<tr><td>Squat</td></tr>
<tr><td>Bow</td></tr>
<tr><td>Jump</td></tr>
<tr><td>Sit</td></tr>
<tr><td>Rotation</td></tr>
<tr><td>Voice command</td><td colspan="2">Sentence</td></tr>
<tr><td rowspan="5">Tools</td><td rowspan="2">Interfaces</td><td>Fixed interfaces</td></tr>
<tr><td>Mobile interfaces</td></tr>
<tr><td colspan="2">Pointer</td></tr>
<tr><td rowspan="2">Others</td><td>Timer</td></tr>
<tr><td>AR</td></tr>
</table>

Table 2 Taxonomy of Interaction

To better understand the interaction of large-scale shape-changing walls, I summarised and analysed data in the following two directions. The first one was to compare interactions in two different zones and between cubes of different sizes. The aim was to investigate whether the zone and size would result in different types of interaction. The second direction was to group the interaction by the tasks and explore the differences with mobile interaction. To illustrate the results thoroughly, I used different data visualization methods. The overview of the interaction usage was shown by heatmap because the frequency could be better visualized by the heatmap. The chi-square test is an efficient method to determine whether there is a significant relationship between multiple different categories. Since the data was nominal, the chi-square test was used to analyze the data. I created extended association plots to visualize the test results because the association plots could well demonstrate the difference of frequencies between categories. In this project, I used chi-square and standard deviations of mean to determine whether the zone and the size of cubes would affect the interaction type.

5.6.1 R language

First of all, I adopted the bottom-up method to code the data so that the data would be appropriately organized and structured. Every input could be tagged by the three categories: body part, voice or the specific tool used. Then, more general groups would be created with the labels: gestures, voice commands and tools. After that, I used the R language to analyze all the coded data. In order to input data into the software, the coded data was saved in the form of CSV, and the first row was set to be the row containing the column names.

To find the possible impact zones and sizes have on interaction, I used chi-square test in R. The function *chisq.test()* was called to calculate the p-value. When the value is smaller than 0.05, the impact is significant. To visualize the results, I also used the function *assoc()*. Additionally, to have an overview of the frequencies of all types of interaction in different conditions, heatmaps were made in R. The function *heatmap.2()* was called to create heatmaps with set colours. Here I chose to use *colorRampPalette()* to design the colour.

5.6.2 Analyze the condition effects

First of all, I grouped the interacting reactions by the three main categories: gestures, voice and tools to see whether the zone could affect the reaction. Gestures were the most commonly used type of interaction in the whole process. With deeper analyzing by the chi-square test, the result (X-squared=96.221, df=2, p-value<2.2e-16) showed that there was a significant difference between the actual frequencies and expected ones in types, which means that the zone could largely influence the type of interaction. As shown in Figure 15, the frequencies of tools and voice used in Zone2 were far more than these adopted in Zone1. This phenomenon may be explained by the fact that the tools and voice would reduce the inconvenience brought by the distance. Participants were more likely to use tools or voice command to control the system when they were 1-1.5m far away from the system.

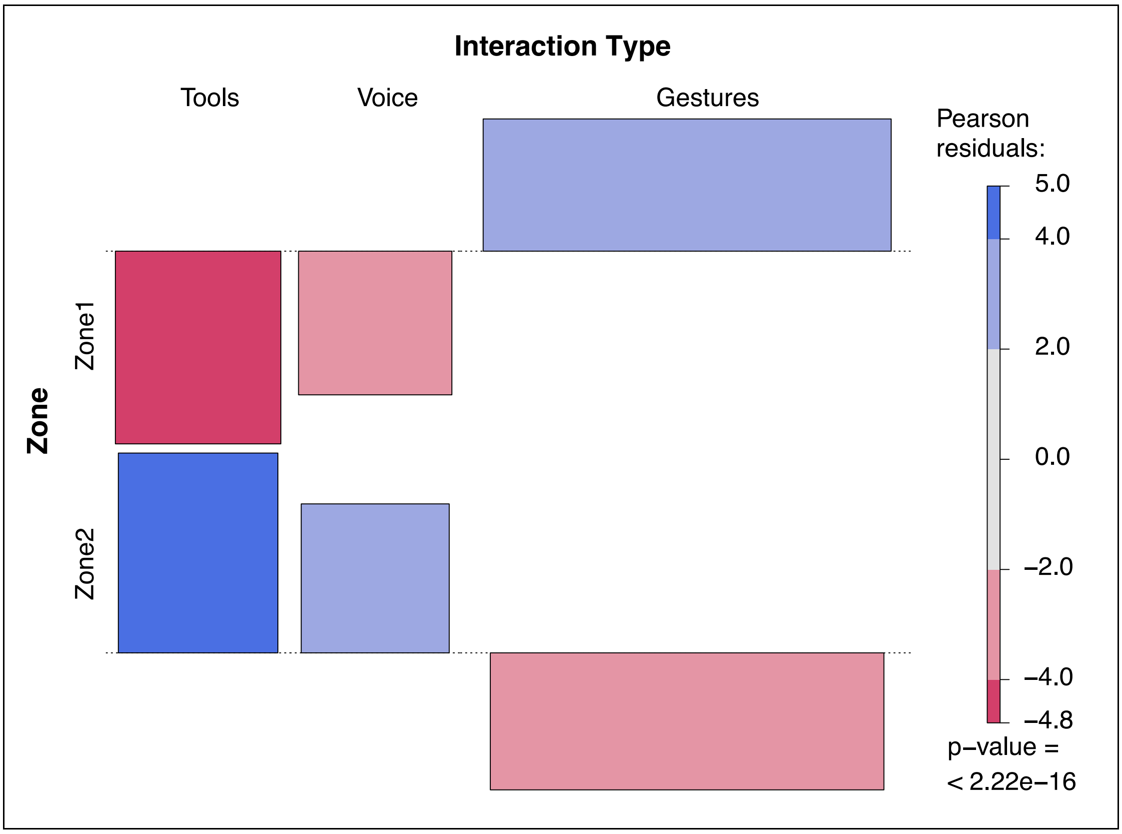


Figure 15 Extended association plot of the interaction type and the zone

In view of that the Voice and Tools had limited subcategories, the detailed comparisons were only conducted for the gesture. Gestures of different body parts were analyzed respectively (see association plots in Figure 16). However, from the figures, the zone did not affect the body part chosen to interact. When deeply analyzing each type of gestures, none of the body parts in these three subcategories showed a significant difference between the expected frequencies and observed ones in two zones. It means that users would not use different types of gestures based on the distance. As for the upper-limb gestures, both in zone1 and zone2, arm gesture was the most popular type. Hands used almost twice as much in zone1 as zone2, probably for the reason that when in zone1, where participants were able to touch the wall, they were more likely to use hand gestures.

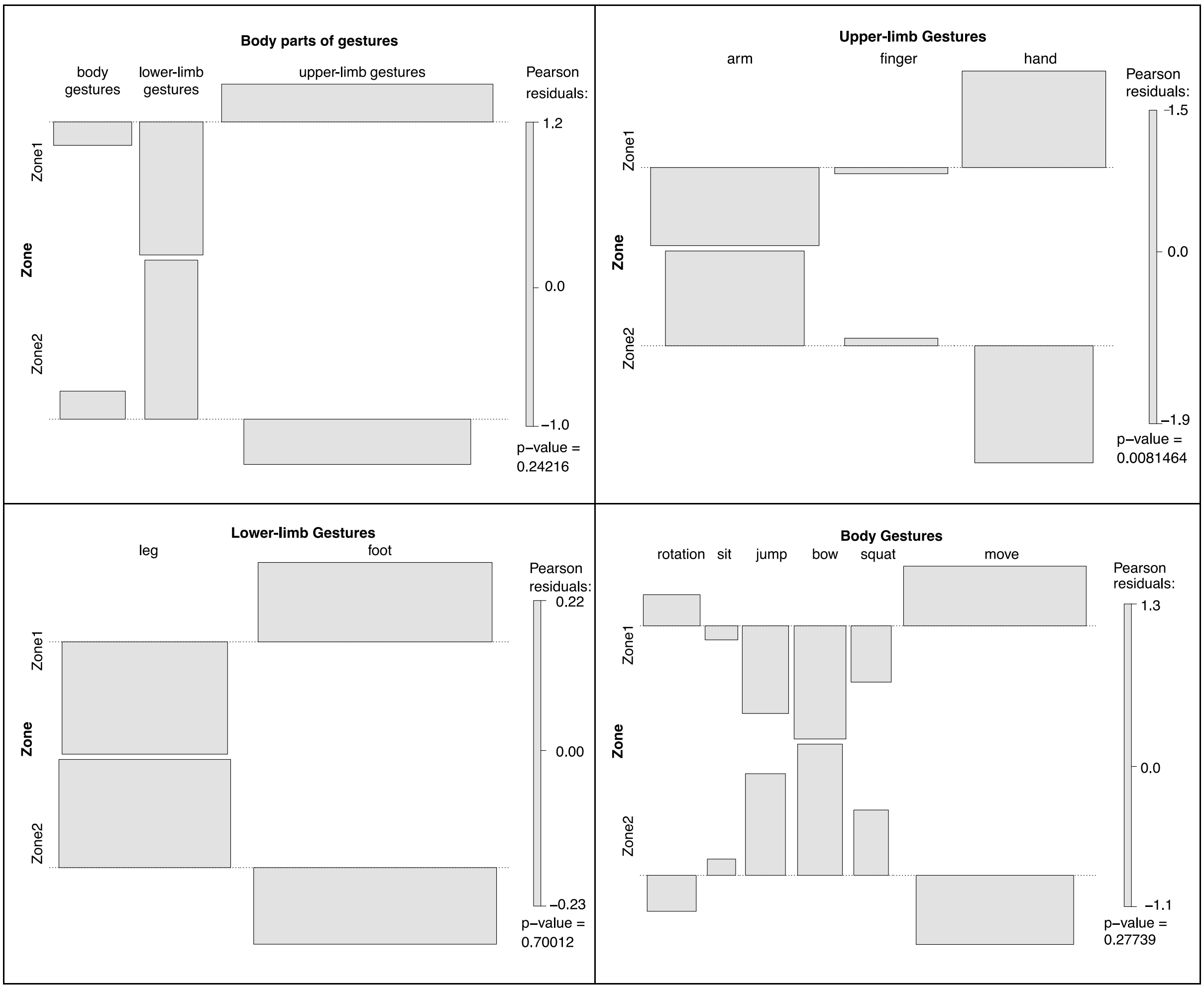


Figure 16 Different gestures used in two zones (from left to right, top to bottom: three types of gestures, Upper-limb gestures, Lower-limb gestures and body gestures)

Then, with the same technique, I calculated and analyzed the possible relation between the size of cubes and the type of interaction. The frequencies were also firstly grouped by the three categories: gestures, voice and tools. The results were not the same as expected. Different sizes of cubes had no significant effects on the interaction choice. The details could be seen in Figure 17.

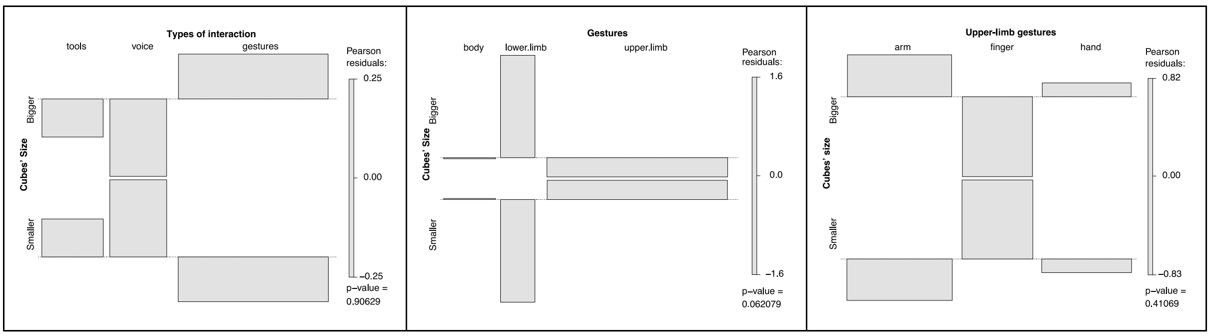


Figure 17 Different types of interaction with cubes of two sizes (from left to right: Overview, different gestures, upper-limb gesture)

Except for the evaluation about the potential influence of zones and cubes' sizes, the analytical approach named standard deviations from the mean was used to determine the frequencies of each reaction in different conditions. In Figure 18, the upper-limb gestures, including hand gestures, finger gestures and arm gestures, were mostly used when participants were in zone1. Lower-limb gestures were popular chosen when volunteers were facing the cubes of the bigger size. The frequency distribution of the body gestures was a little complicated. Body movements and body rotation often happened in zone1, while the squat, bow and jump motions happened in all conditions except the combination of zone1 and smaller cubes. Voice command and tools were mostly adopted when participants were in zone2.

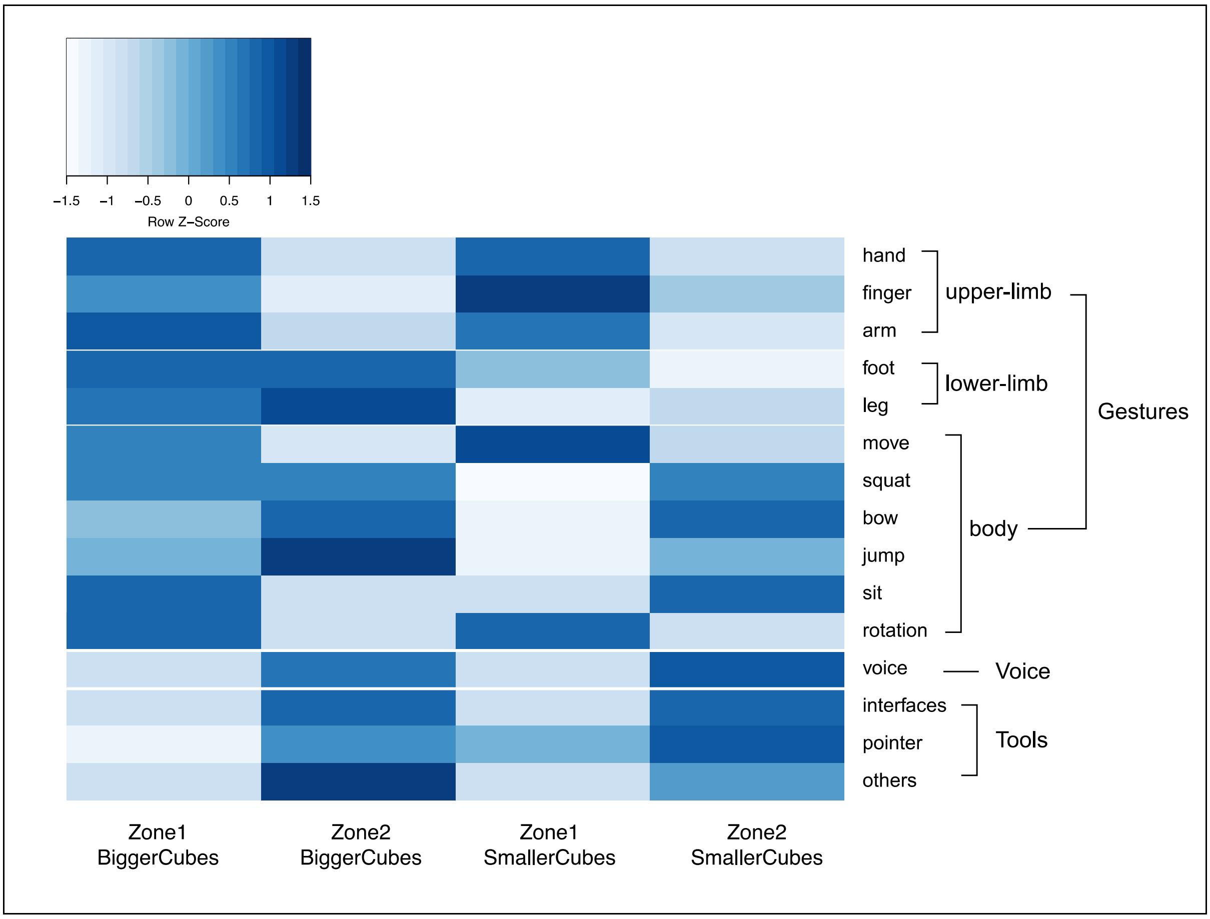


Figure 18 Frequencies of interaction used in different conditions

5.6.3 Analyze the types of interaction by tasks

For each task, the various commands were found. There were totally four times that participants gave up the tasks. The tasks included form a pattern in the upper side of the system in zone1, reflect the pattern of smaller cubes in zone1 and reverse the pattern of smaller cubes in zone2. Because the volunteers were implementing the think-aloud method in the tasks, the reasons were explained as follows: 1. They had no idea what to do without touching the system at once, 2. It was too difficult to achieve the tasks, 3. They had no previous experience to refer to.

To get the general view of the frequencies, I visualized the distribution with heatmap. In Figure 19, by estimating the usage of every command, I found that people preferred to make similar gestures to the transformation of the pattern. For example, the body movement was mostly triggered by moving the task which was designed to make participants move objects. In the study, volunteers would likely to walk from the original position to the targeted position or move their bodies to get close to the place with or without consciousness. One participant even chose to jump to the set position. Similarly, when volunteers adopted the bowing gesture, they were probably dealing with the pattern in the lower part of the system.

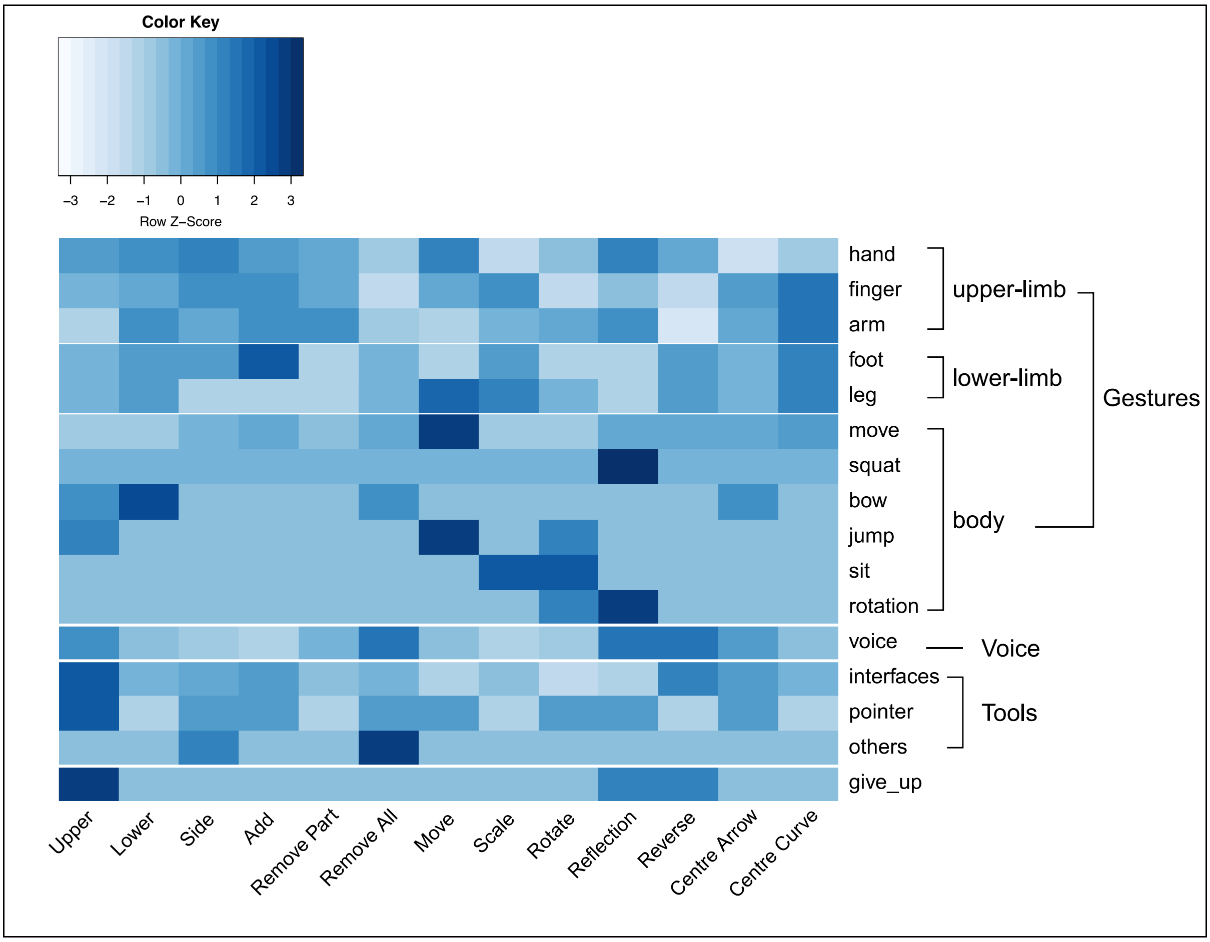


Figure 19 Commands used in different tasks

In order to statically determine whether the tasks would define the type of commands, I used the chi-square test to analyse. Since the numbers of tasks in each category were not the same, I used the average times each type adopted in the study to do the calculation. The results indicated that the tasks would not influence the choice of gestures, voice command or tools. Moreover, when estimating the impact of tasks on the most often used body part – upper-limb, the p-value was 0.8249, which was quite larger than 0.05.

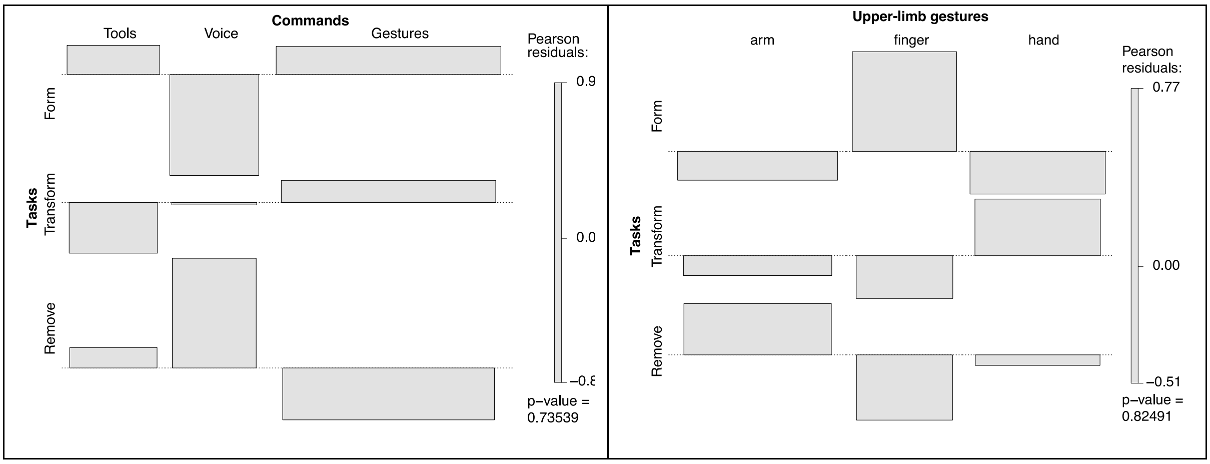


Figure 20 Different commands used in diverse tasks

Despite the voice commands and tools usage, gestures were diverse for each task. To investigate whether they shared things in common, I concluded the gestures in a table. It was important to note whether the commands were delivered by static postures or in the dynamics. Furthermore, the frequencies of all gestures were evaluated. The performance of participants was described in Table 3. The frequencies were the sum of times participants used that particular gesture for in every different task under two conditions.

Task		F	Gestures	S/D	N
Form	Upper	35	1. Draw with fingers	D	5
			2. (1), and push it up with one hand	D	11
			3. (1), and pull out with one hand	D	4
			4. (1), and pull out with two hands	D	10
			5. Touch with one hand and push it up with one hand	D	1
			6. Draw with fingers on the ground	D	2
			7. Drag feet in the path with the same shape	D	2
	Lower	51	1. Touch with one hand	D	11
			2. Draw with fingers	D	7
			3. Draw with one hand	D	15
			4. Squat and (3)	D	2
			5. (2), and double tap to pop out cubes	D	2

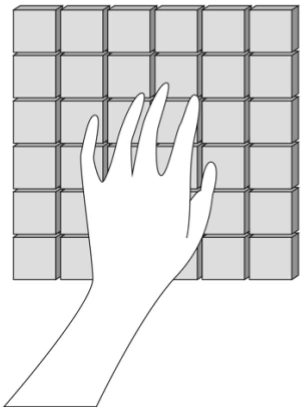
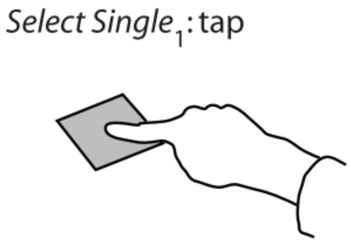
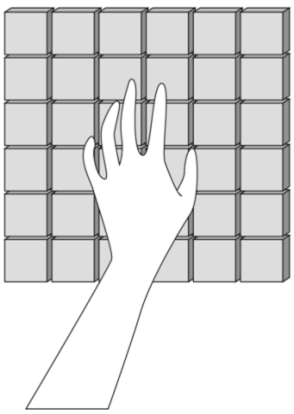
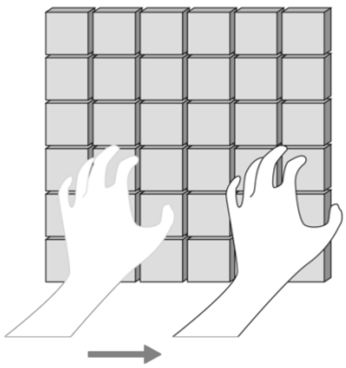
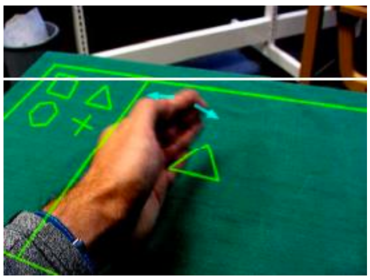
			6. (2), and pull out with hands	D	10
			7. Jump in the path with the same shape	D	2
			8. Drag feet in the path with the same shape	D	2
	Side	42	1. Touch with one hand	D	10
			2. Draw with fingers	D	5
			3. Draw with one hand	D	9
			4. (2), and double tap to pop out cubes	D	2
			5. (2), and pull out with hands	D	12
			6. Index finger and medium indicating width, and move along the path with one hand	D	2
			7. Drag feet in the path with the same shape	D	2
	Add	43	1. Touch with one hand	D	11
			2. Draw with fingers	D	4
			3. Draw with one hand	D	9
			4. (3), and pull out with one hand	D	6
			5. Pointing the turning points with the index finger	S	1
			6. Draw with index finger and double tap to pop out cubes	D	2
	Curve	43	1. Draw with fingers	D	13
			2. Draw with one hand	D	9
			3. (2), and pull out with one hand	D	5
			4. Draw with two hands	D	4
			5. Touch with one hand	D	8
			6. Draw with index finger and double tap to pop out cubes	D	4
Transform	Move	40	1. Move fingers to the position	D	4

			2. Move hands to the position as if carrying the object	D	6
			3. Grab and move to the position	D	4
			4. Tap to select and drag with one hand	D	11
			5. Use the palm (perpendicular to the interface) to push objects to the position	D	9
			6. Draw a circle to select objects with index finger, and grab to the position	D	2
			7. Face the target object and then jump to the position	D	4
	Scale	38	1. Both palms squeeze together	D	22
			2. Index and thumb stretch from old size to new one	D	3
			3. Index, thumb and medium fingers squeeze together	D	2
			4. Open palm	D	7
			5. Tap to select, and then do (2)	D	2
			6. Jump and open the feet	D	2
	Rotate	40	1. Rotating index fingers	D	4
			2. Rotating two palms as if manually rotating	D	23
			3. Grab two ends of the object and rotate	D	4
			4. Twist with one hand	D	7
			5. Sit down and rotate body	D	2
	Reflection	27	1. Flip. One palm rotate around the wrist	D	10
			2. One palm still and the other move from left to right	D	4
			3. Select with index, grab, and flip the fist	D	2
			4. Select with index, and flip two fingers	D	2
			5. Select with hand and turn body around	D	2
			6. Press back and draw a new one	D	5

			7. Mimic the shape by the body and do reflected gestures in target position	D	2
	Reverse	19	1. One palm still and the other palm moving in	D	4
			2. One palm still and the other palm pulling out	D	4
			3. Turn one hand over	D	2
			4. Pushing in for a while	S	9
Remove	Part	39	1. Select with fingers and wipe	D	7
			2. Select with index and drag outside the edge	D	4
			3. Press back	S	28
	All	23	1. Wipe with one hand	D	13
			2. Select with fingers and press back	D	10

Table 3 Commands in tasks (F=Frequency, S/D=Static/Dynamic, N=Frequency of the particular command)

There was a few research focusing on the gestures of digital interfaces. To compare the differences of gestures performed with shape-changing actuated systems and the digital ones, the gestures of digital surfaces were collected(Nielsen *et al.*, 2003; Wobbrock *et al.*, 2009; Niiro *et al.*, 2019). For the reason that the functions of digital screens were different from the shape-changing surfaces, several selected gestures were compared. They were: 1. Select, 2. Draw/form a shape, 3. Transform a shape (move, scale and rotate) 4. Delete/remove a shape. The picked gestures of shape-changing actuated system were the most common ones among all the gestures. Also, another point to state is that though only 35% of participants used the select gestures, it was valuable to investigate the differences between the gestures of simple tasks.

		Dynamic actuated interfaces	Digital Interfaces
Select			 (Wobbrock *et al.*, 2009)
Draw			 (Niiro *et al.*, 2019)
Transform	Move		 (Nielsen *et al.*, 2003)

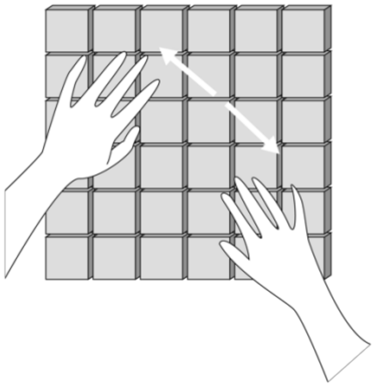
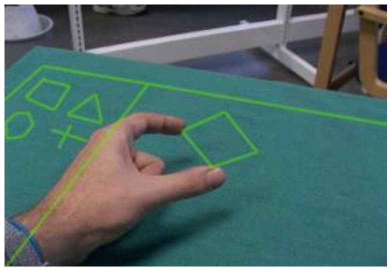
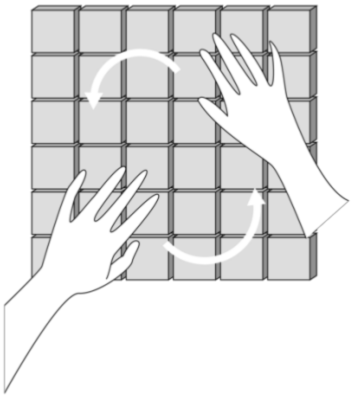
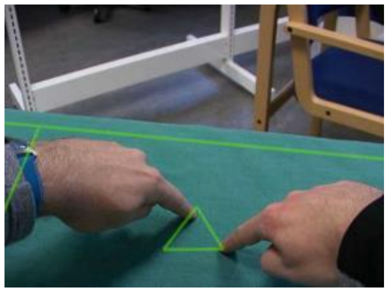
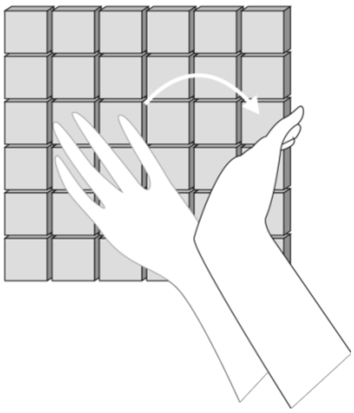
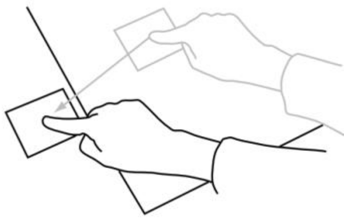
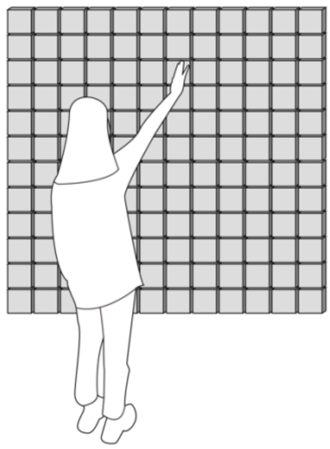
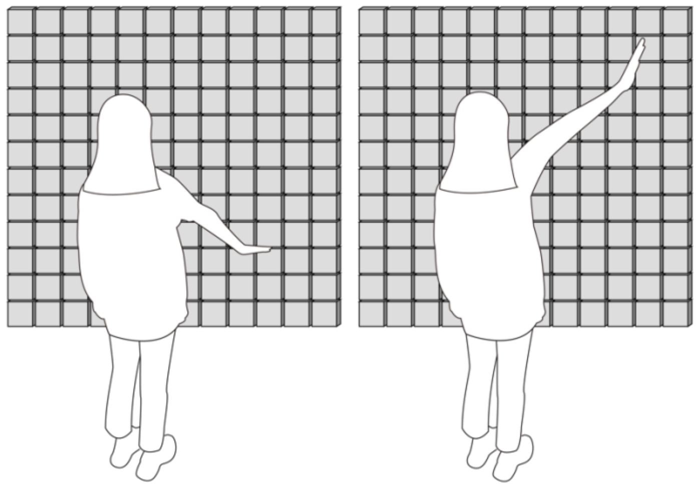
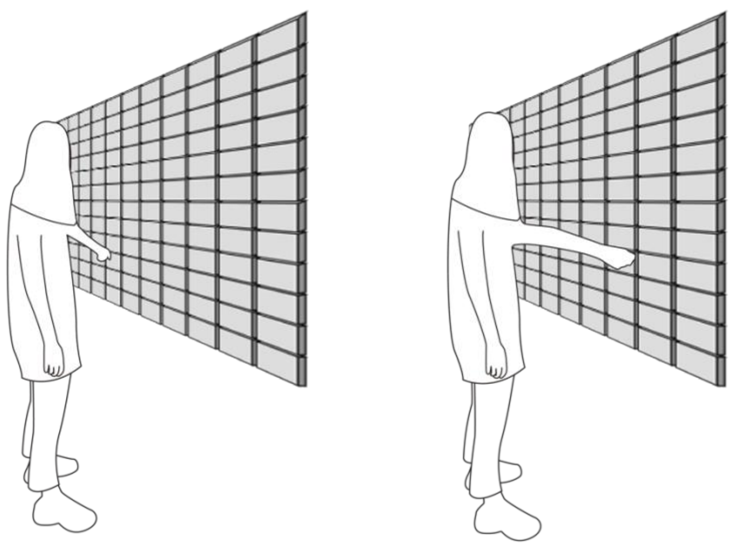
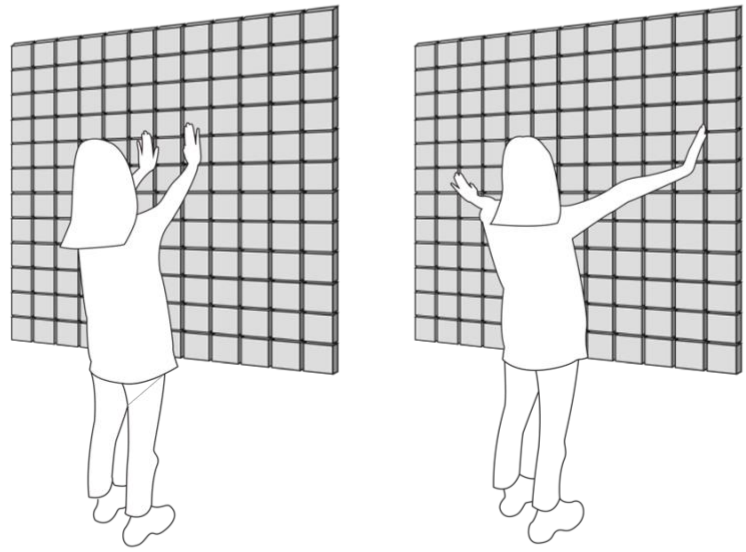
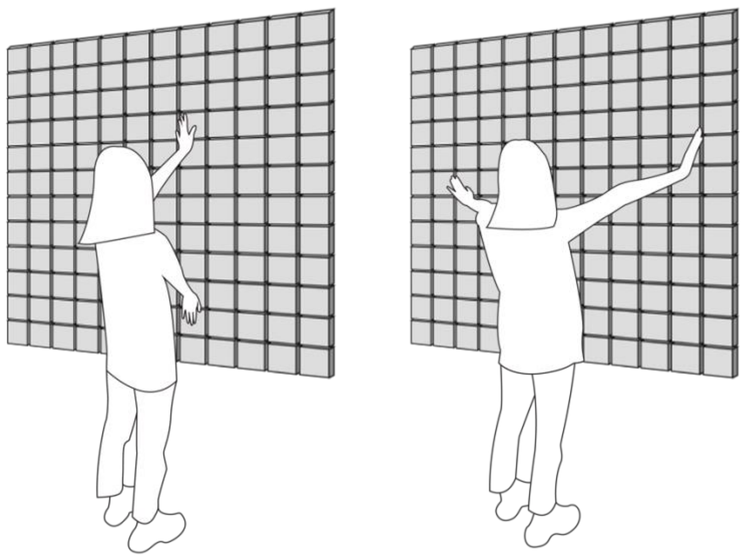
	Scale		 (Nielsen *et al.*, 2003)
	Rotate		 (Nielsen *et al.*, 2003)
Remove			 (Wobbrock *et al.*, 2009)

Table 4 Comparison of different interfaces' gestures

Different from the gestures with tabletop surfaces, a large part of the interactive gestures with wall systems was body-based gestures. Participants would get closer to the wall when the pattern was small and rich in details, while they would choose to step back when the shape was large, or they could not reach some of the cubes. Thus, I reproduced the gestures most participants performed in the study (see Table 5).

		Gestures interacting with dynamic actuated interfaces
Select		
Draw		
Transform	Move	

	Scale	
	Rotate	

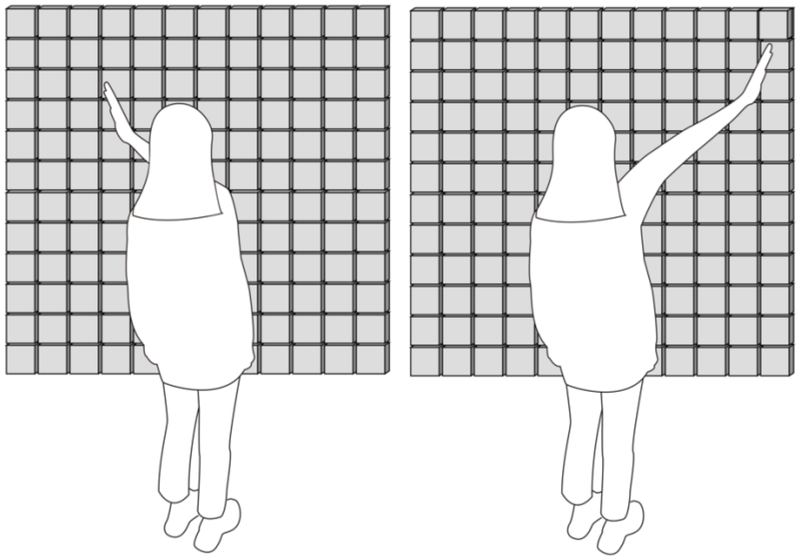
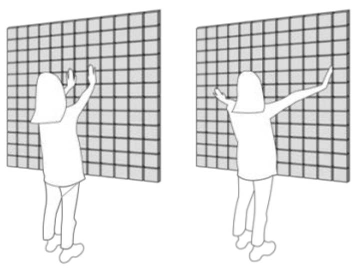
Remove	

Table 5 Body gestures of different tasks

Along this line of consideration, the body-based gestures were also deserved investigating. Most of the previous research has focused on body gestures' recognition, but few work has been done on the gestures set because the scenario was mostly in the game. Below is a table aimed to compare the gestures in different scenarios. The gestures set in the storytelling scenario was collected from (Kistler e André, 2013). Because the virtual environment was set to be in a bar, the required space was supposed to be bigger than the interaction space of shape-changing wall systems. However, as it was shown in the table, people tended to make smaller gestures in the storytelling scenario. The reason could be that the closer the virtual scene was to reality, the more significant gestures people would like to do.

	Gestures set in interactive task accomplishing scenario	Gestures set in interactive storytelling scenario
Scale V.S. Ask for directions		

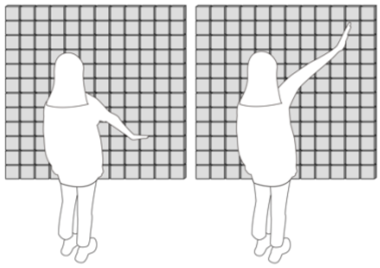
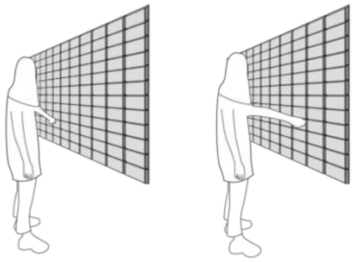
Finger draw V.S. Point to someone/ something		
Move V.S. Approach		

Table 6 Comparison of gestures in different scenarios

As it was shown in Table 4, the gestures of shape-changing vertical systems had been affected by the digital ones as movement directions were similar. The digital interfaces were usually relatively small, and thus, fingers were used heavily. When it refers to large-scale surfaces, hands and arms became the most commonly used parts. Meanwhile, people's bodies would make related gestures according to the tasks.

Apart from these similar gestures, there were several impressive commands sent by participants. The first one was to pretend to use a feature. For example, when a volunteer intended to form a chair, he or she would make the sitting gestures. Another interesting interaction was to use the ground as a static interface. A case in point was one participant dragged feet in the same path as the pattern in the system.

5.6.4 Results of the interview

The interview helped to better understand the result of the interaction. To analyse the qualitative data, I adopted the inductive approach and used thematic analysis (Given, 2008). The induction is a bottom up approach which was suitable in my case where I aimed to deepen understandings and seek problems. First of all, I went through the logs and videos of the interview. Then, in units of each question, every sentence was written down in details. After that, I put labels on every answer and grouped those similar ones. Next, focused coding was performed in order to get readable and unique codes. Last but not least, I summarized the keywords in the form of word clouds.

As for the differences between the interaction in two zones, 80% of participants preferred to touch the wall when they were in Zone1, which was the closest zone to the wall. Two participants mentioned that the motion would change according to the materials of the wall. If the surface were clean and smooth, they would touch the wall. Another participant said Zone1 made him more engaging while touching the wall. An interesting phenomenon was that about 20% of people considered the gestures and motions would be more in Zone1, while 10% of volunteers thought that more significant gestures would be used in Zone2. One reason mentioned by the 20% was that in Zone1, shapes in different positions would require different gestures and standing points, while in Zone2, they preferred to stand in a set position. Another reason claimed was that they would prefer to use one hand rather than two in Zone2. Since participants were unable to touch the cubes in Zone2, 30% stated that they would be more likely to depend on tools, and 10% would prefer to use voice command. A popular idea mentioned by 30% of 20 participants was that standing back gave them a more general view, and they could form complex shapes with better interactive experience.

Figure 21 Word Clouds for interviews about two zones (from left to right: zone1, zone2)

When referring to the difference between the interaction with cubes of two sizes, 30% of volunteers said the wall with smaller cubes was hard to draw precisely. In contrast, 5% of participants thought the bigger cubes were more precise to frame. On the other hand, 35% mentioned that smaller cubes could express more details. To better describe these details, one would prefer to use fingers, and another two preferred to use tools. One participant even brought up the idea that the wall consisting of small cubes gave him similar feelings as a digital screen. Considering the ability to express more details, 10% of participants thought that the smaller cubes could form a static decoration with smooth curves. Also, one volunteer preferred to operate in the distance facing smaller cubes because he wanted a full view. As for the wall with bigger cubes, 35% of participants thought the movement was more realistic and palpable. Thus, they knew better what to do. 10% of people considered the cubes were more like furniture. In view of the gestures, 15% mentioned they preferred to use the full hand.

Figure 22 Word Clouds for interviews about two sizes of cubes (from left to right: smaller cubes, bigger cubes)

60% of people used gestures a lot, while 45% of volunteers applied interface s considerably. Voice commands were adopted as the main control method by 20% of participants. When asking about the reasons why they chose the particular type of interaction, people who used gestures a lot mentioned the following reasons. 20% of people had experience in operating digital screens, and similar gestures would be applied in using the wall system. 15% of participants chose to use gestures because of the physical objects and 10% referring to the movement of cubes. Also, 10% of volunteers said the gestures were easy to do, and they were immediate commands. One participant used foot gestures incredibly for entertainment. Another 10% used gestures because they were not limited by distance. Among the people who took interfaces as the primary type of interaction, 66.7% regarded that the interfaces were more precise compared with gestures. 33.3% of them thought it was more efficient because the interface with storage disks could store basic patterns and be customized. Other reasons mentioned were: computers were frequently used in daily life; interfaces were not limited by the distance; operating computers made no noise. Voice command was favoured because of its convenience and fast expression.

Figure 23 Word Clouds for interviews about reasons to use gestures and interfaces

The last question asked in the interview was the difficulties and problems that participants could think of when interacting with the wall system. Two most frequently mentioned problems were: 1. Got confused when being unable to touch the moving cubes; 2. Be concerned about the accuracy of gestures. Both of them were mentioned by 40% of the participants. One participant emphasized particularly on the case when the cubes were small, and the user was required to stand far away from the wall. 10% of people thought that the gestures were similar and may not be recognized correctly. About 15% of participants were concerned about the efficiency of the voice command since it was hard to describe the exact shape as expected. One participant found that the selection was difficult when he wanted to choose a specific shape to moderate. Last but not least, 10% of volunteers would like to have a visual aid to help with confirmation and tracking.

Figure 24 Word Cloud for the difficulties or problems

6. CHAPTER 5: DESIGN SESSION

The last user study was aimed to explore participants' interaction input, and in this section, I would introduce a simple in-lab design session targeting to investigate the preferred interaction output of the system. Three fundamental dimensions of the feedback were tested in the study: popping order, speed and response time, which were derived from the feedback of participants in the elicitation study. Among them, since the proper speed was hard to control, the movement completion duration was evaluated. I adopted the methodology for the elicitation of formative preference, and the think-aloud method was approached in the study.

6.1.1 Prior study

In view of the fact that there were no related studies about the shape-changing movements, I conducted a pilot study to have general information about people's preference towards the movement and to determine the testing conditions. In the study, two participants were recruited. Firstly, they were asked to pull out the blocks at their favourite speed. It turned out that they both moved the component out for around 1.5 seconds. In consideration of the size and its moving distance, the shifting speed would be roughly 12cm/s. In this case, three periods of moving time were designed to be less than one second, 1.5 seconds and 3 seconds. Also, I tested how long was a reasonable delay for those two participants. It seemed that they did not want any delay. Meanwhile, considering the reaction time of the researcher, the response delay was set to be 0 seconds, 1 second and 2 seconds.

6.1.2 Task

The evaluated scenario was set to be the same as the one in the elicitation study. The task was to require participants to assess the most intuitive way to move out the blocks. First of all, the expected pattern was shown, and participants were asked about the favourite order in which the blocks started to move. Based on the answer, a demonstration of cubes with the same popping order was displayed to familiarize volunteers about the system's functions. Then, detailed movements of blocks were investigated. As stated in the prior study, three speeds and different system reaction time were to be tested. The periods of completion time were less than one second, 1.5 seconds and 3 seconds. Besides, as for the system reaction time, after participants sending the commands, the system waited for 0 seconds, 1 second and 2 seconds respectively. Thus, the forming process was repeated for $3 \times 3 = 9$ times.

6.1.3 Participants

I recruited 6 people (2 male) from the local university to participate in the user study with a mean age of 22.67 years. They were from two different academic backgrounds: 4 in computer science, and 2 in human computer interaction. None of these participants had previous experience of interacting with shape-changing wall systems.

6.1.4 Materials

Instead of using a projection like in the last study, I used storage boxes on the shelf as the mock-up to do the study. The movements of the boxes were manually operated by the researcher from the back. To control the speed, tick marks were added to the boxes and a timer was used during the whole process. The feedback and reactions of participants were audio-taped by a mobile phone.

Figure 25 The mock-up wall

6.1.5 Procedure

The user study began with a 5-minute introduction demonstrating the purpose of the study. Then, the pattern was shown to participants, and they were asked about their preferred moving order. The question was: In which order would you think is the best for these components to move in order to form the shape? The reasons were asked as well. After that, volunteers were required to use the prescribed gesture (touch the cube) to give commands for three times. On receiving the command signal, the researcher who hid behind the wall would move the box in one of the three speeds. The speeds were randomly ordered, and after finishing all three-speed tests, the participants were asked to choose their favourite one. Then, to test the system reaction delay, participants were required to make the gestures again for three times. Unlike speed testing, the researcher started to perform the movement with a specific delay, which was one of the three to be tested. The testing order was randomly assigned as well.

Volunteers were requested to vote for the most comfortable action delay. The reasons for choosing the particular speed and delay time were asked.

6.1.6 Results

The results could be seen in Figure 26. As for the moving order, 50% of participants would prefer the blocks of the pattern to come out together because they hated to wait, and they had already got a clear idea of the shape. One participant preferred the pattern to form from the centre to edge since the system reminded him of the wave. Other 33.3% of participants favoured the cubes to start to move in the same order with the hand movement. It was surprising to find that all the volunteers choose the midden speed: 12cm/s. The reasons were that popping out too fast would scare them, and when the speed was too slow, they would easily get impatient. In this case, a moderate speed was acceptable. Things were different when it came to the system reaction time. 66.67% of participants preferred no delay at all, while the others preferred to have a short delay like less than 1 second because they did not like a sudden.

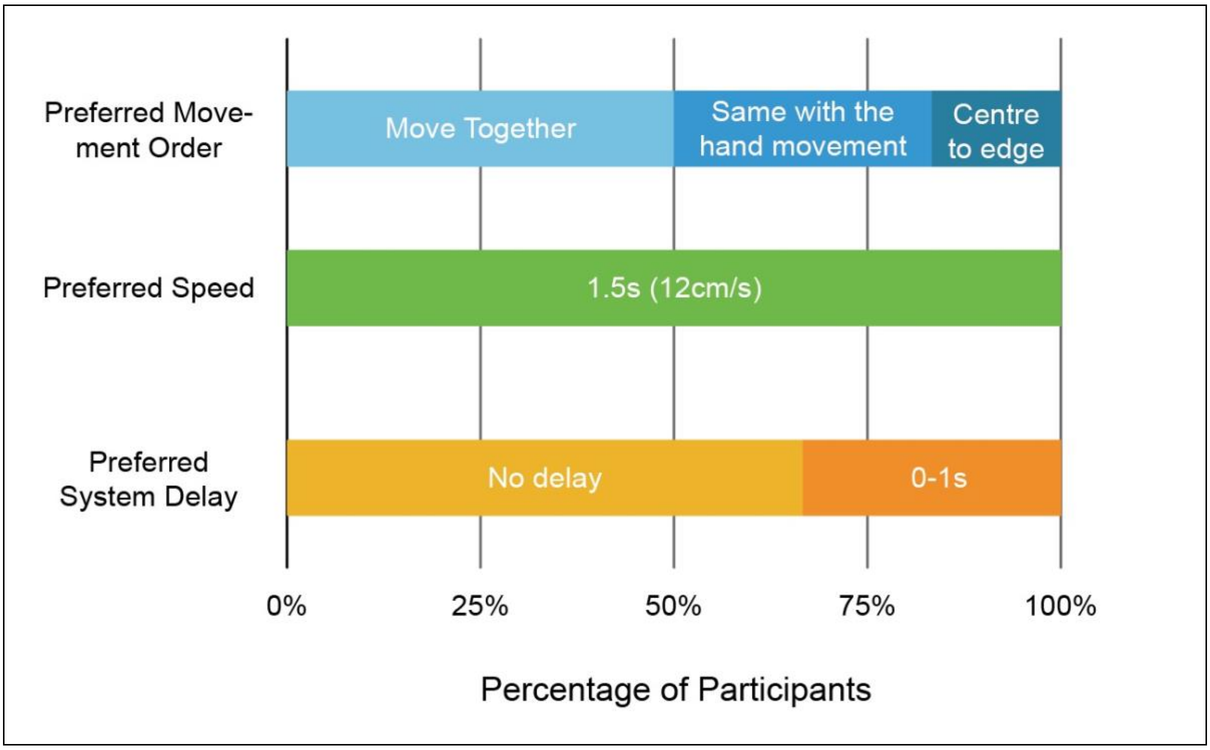


Figure 26 The Results of the Design Session

7. CHAPTER 6: DESIGN AND IMPLEMENTATION

7.1 Introduction

In this project, a small scale of shape-changing wall system was made to prove the concept. In consideration of the fact that the preferred interaction varied individually, sensors and interfaces were not implemented in this prototype. The mock-up consisted of 2 × 2 components and every block could move individually. To achieve the prototype, Arduino was used as a controller, and 3D printing technology was applied to build the model. The model was able to display different shape forms.

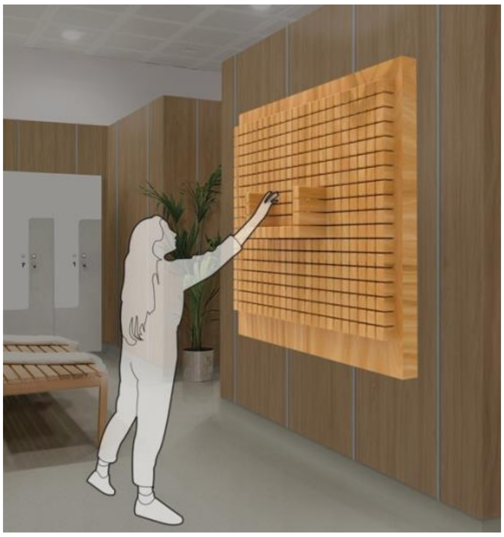


Figure 27 The rendering of the system

7.2 Structure Design

The primary function of the shape-changing wall is to allow every component to move in and out. The original status of the system should be a plain wall. In the beginning, the structure of ballpoint pens was considered because cubes could pop out and return back by pressing. Nonetheless, the interaction was limited to the touch type. To avoid this, a more flexible approach was adopted. As it was stated before, the system required all cubes to start from a vertical plane. It means that adding a power source like motors would be available as long as all the motors are static and arranged on the same plane during the whole process.

Therefore, the structure of every component is designed to have one motor, one screw and one cube (see Figure 28). The motor is supposed to drive the screw, and the screw drives the block forward and backwards when rotating. The cube is, therefore, moving in and out, and could stop at a specific place. To move cubes horizontally, screws are displayed in the same direction.

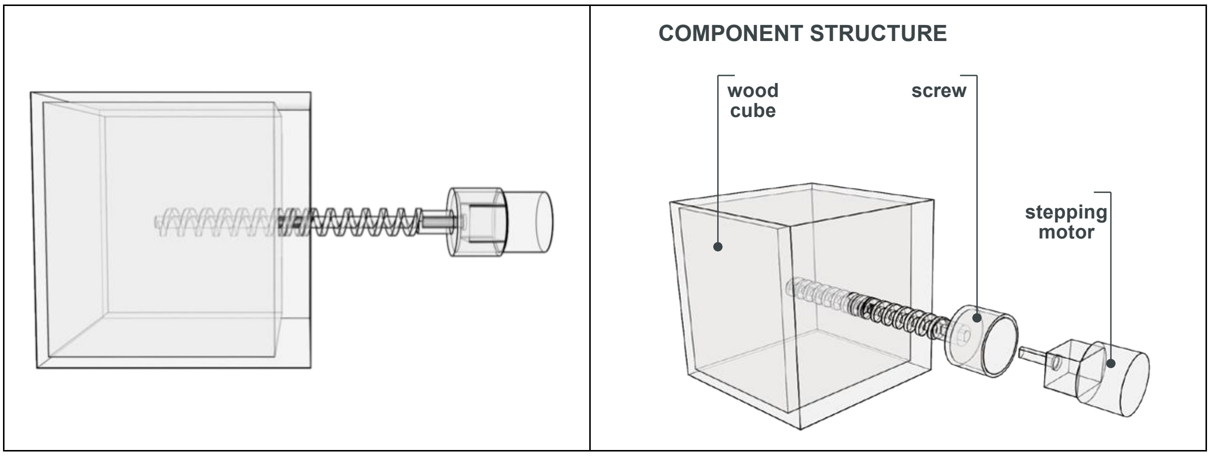


Figure 28 The translucent structures

There are several aspects to consider when designing the structure. One is the power of the motor. The motor has to overcome the friction and make the screw rotate. Furthermore, because cubes are moving horizontally, the screw needs to bear the load of cubes, which increases the friction. Another factor to concern is the measurements. The size of the cubes would affect the weight, which has an effect on the friction. Also, the thread length and the pitch of the screw would decide how far the cube could reach. To better use the space, the length, number, pitch of the thread need to be carefully calculated. Last but not least, the installation demands a precise connection structure. For example, the screw must rotate with the motor.

7.2.1 Hardware

Because the prototype was aimed to be concept-prove, the hardware mainly included two parts. One was the control module which sent commands to and controlled the system. The other part was to drive the components to move. In the future, sensors and a mobile interface would be added to the system.

7.2.1.1 Control Module

There are mainly two widely-used control modules in the design field: Arduino and Raspberry Pi. Both of them allow for data communication and appliances controlling. In the first stage, Arduino was chosen to do functionally testing because of its portable and lightweight.

To control the direction of the movement, a button was set to give instructions to the driver. Arduino was responsible for getting the signal of the button and sending commands to the motor (see Figure 29).

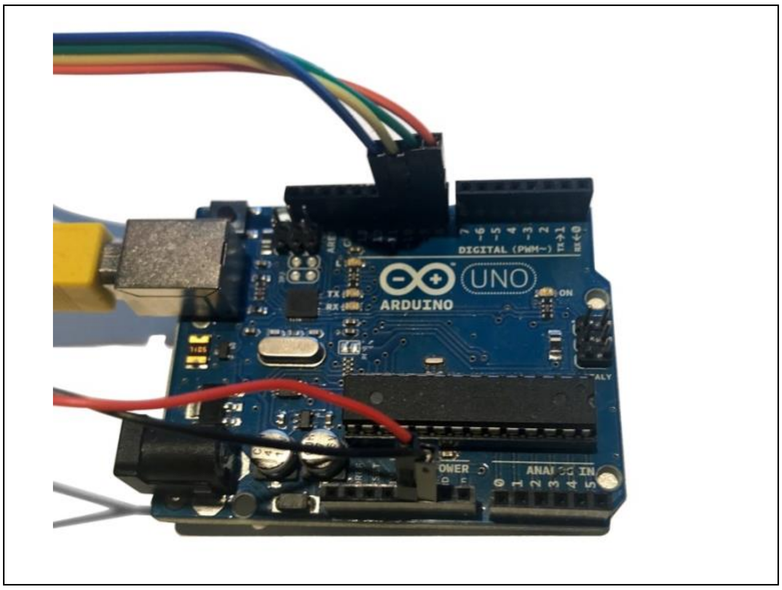


Figure 29 Arduino Board used in building a model

7.2.1.2 Drive Force

At first, servomotors were chosen because they were relatively lightweight and only had two cables for the control signal and power. Moreover, servo control boards could manipulate multiple servos at one time, such as Adafruit 16-Channel 12-bit PWM/Servo Driver. It was beneficial for a large scale wall system which contained a number of servos. There were two types of servomotors which have single gear. One was the positional rotation servo, and the other type was continuous rotation servo. These two types were similar except that the continuous rotation servomotors could turn in either direction indefinitely while the positional rotation servomotors could only rotate in a circle. In consideration of the fact that the screw should be able to rotate in both directions, continuous rotation servos were used for testing. However, the gear in the motors was not ideal for fitting with the screw because the requirement of accuracy was too high. For this reason, servo horns were attached to the motor, and the screw was designed to match this shape. However, due to the friction, the cube would rotate with the servomotors, and it was inconvenient to prevent it. It was because that the servomotors were small and could not bear the torque load.

Then, a stepper motor integrated with a lead screw was considered because the structure was easily accessible. Besides, the motor could definitely provide enough power to drive and hold the screw. However, the plan was quickly abandoned in view of the high price.

After that, a stepper motor was used to drive the screw because it had an irregular shaft which could produce a better connection with the screw. Also, the stepper motor was able to provide more power to drive the screw. Moreover, there were two holes beside the motor, which allowed for controlling the cube's moving direction. Nonetheless, four pins were required to control a stepper motor. In this way, to control four motors, at least two Arduino Uno boards were expected, which would inevitably lead to a heavy load. Therefore, an Arduino mega board was adopted in the end.

7.3 Model Building

After solving the problem about the driver, there remained two parts of the component: the cube and the screw. The cubes were required to be in the same size, and the screw was supposed to support the weight of the cube. To create the customized design, several ways were adopted including the laser cutting and 3D printing. One main function of the system was to act as furniture, and it needed the cubes to have strong load capacity. After comparing these two methods, 3D printing was chosen for the prototype.

7.3.1 Laser Cutting

At first, cubes were made by laser cutting. It was an efficient way to get multiple cubes. The outlines of the cube's six faces were drawn in Adobe Illustrator, and a big hole was dug in the back side for the screw to pass through. Because the screw should rotate, the pitch needs to be slightly larger than the width of the wood board. It was too demanding to form a smooth rotation owing to the rectangular edge. Therefore, the model was designed to be built by 3D printing, which gave the cube much plasticity.

7.3.2 3D Modelling

Both the cube and the screw were modelled in 3D modelling software, and Rhino was used in the project. To reduce the load of motors and accelerate the iteration speed, a relatively smaller cube of 5×5 cm was built and tested. Furthermore, the cubes were designed to be hollow to save the materials and reduce the printing time. In order to save space, an external screw thread form was applied rather than the internal one. The pitch could not be too narrow because they were the essential part to force the cube to move. Moreover, the major diameter of the thread should not exceed 1.5 times the minor diameter in case that the thread would be easy to break off. In this case, the crest flat was designed to be 4mm, and the flank was 5mm. To guarantee that the screw could fit into the cube, the female thread shared the same rail with the male thread but had a slightly larger curve. This was because of the accuracy of the printer. The measurements of the servomotor were carefully measured, and the model was rebuilt in the Rhino. Boolean difference command was performed in the screw to match the shape of the motor. The juncture was set to be in the centre of the screw and the cube so they would not move in the horizontal direction.

7.3.3 3D Printing

The key to the 3D printing is about the materials and the support settings. The most common material for printing was generic PLA (Polylactic acid) which is a kind of bioplastic. Because the structure of the screw is dedicated, the PLA was not suitable for the support. If the support used PLA, when it was peeled off, the thread would have rough surfaces which could make the rotation harder. In order to help with the peeling and rotating process, another material was used to form the support. That was Natural PVA (Polyvinyl acetate), which was soft and easy to be stripped. Moreover, the orientation of the objects is essential as well. It is because that the printer started the building work from the print bed and formed a first layer support extension automatically. In this case, taking the face with the matching hole as the bottom was not appropriate. At first, the model was put on the side to print. However, since part of the thread contacted with the print bed, the thread was not smooth and strong enough. Then, the screw was put vertically, and the first layer support was chosen to be brim.

7.4 Installation

First of all, the screw was rotated into the cube. To guarantee that these two parts could match each other, a sickle was used to smooth the thread. After that, the screw and the servomotor were buckled. However, due to the high friction, the cube rotated with the screw rather than move vertically. In order to solve this problem, two thin steel rods were added to the component. It was convenient to connect the rod with the servomotor because the motor had two holes on the side. To insert the rod into the cube, an electric drill was used to drill two holes in corresponding positions with motors on the cube. After completing these, the cube could move in the same way as expected (see Figure 30).

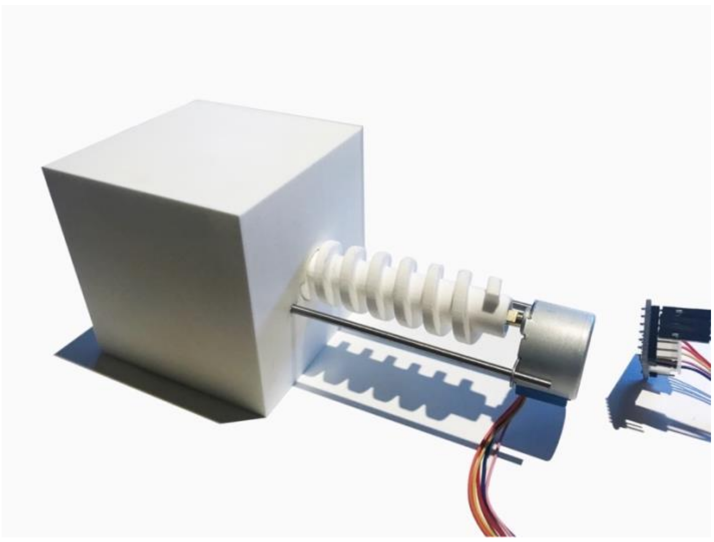


Figure 30 One component of the mock up

8. CHAPTER 7: CONCLUSION

8.1 Results and analysis

The project investigated people's preference for the interaction with shape-changing wall systems, which was aimed to help with the interaction design. Different from the digital screens, the dynamic actuated systems allowed for tangible physical interaction and had extended functions like serving as furniture. Although in this project, I had not yet conducted a formal evaluation of the specific performance of every interaction technique, the intuitions of the input were carefully studied through the elicitation study.

After finishing the training session, all users were quick to react to the system and picked the proper interaction techniques for tasks intuitively. Despite the fact that the range of motion was noticeably more extensive, the gestures used in operating the system were similar to the ones used with touch-surfaces. It was mainly due to users' familiarity with tabletop displays. The described usage methods of tools to control the system were mainly associated displays, including mobile interfaces and wall-top interfaces. A number of studies about gestures of mobile interfaces have been done (Nielsen *et al.*, 2003; Malik *et al.*, 2005; Epps *et al.*, 2006; Wobbrock *et al.*, 2009), and as participants described in the study, the mobile interfaces gestures were the same. Additionally, the voice commands varied in detailed sentences but the structures of the commands were the same. The structure was 1. Describe operation 2. Describe the shape 3. Describe the position. In this case, the interaction of using tools and voice control would not be discussed in depth. To facilitate the gesture interaction design for such dynamic actuated systems, I would provide a gesture design guideline and recommendations for interaction design.

8.1.1 Guideline for gestures design

The following guideline was designed for instructing gestures design. The dimensions of the guideline were referred to the ones of the brainstorming cards.

Dimension	Guideline
Residents & visitors	Take people of different heights and the disabled into considerations
Activities	The moving speed should be moderate
	Support the instant response
Measurement	Enable users to touch to interact
	Allow for gesture interaction in a distance

	Maintain to provide a sense of substance
Materials	Use clean and smooth interfaces to attractive people to touch
Environment	Provide the visual aid to support the tracking and user confirmation
	Provide associated displays for remote controlling

Table 7 Guideline of the interfaction design for dynamic wall systems

8.1.2 Recommendations of the interaction design

8.1.2.1 Make use of the environment

A critical finding of the study is that the surrounding environment has great potential in helping with the interaction. Because the system was large-scale, users were unable to reach every cube in the system. In this case, the area beside and in front of the surface becomes essential. Thus, a sidebar of the surface or an associated display allocated on the side could work. Apart from these standard practices, another interesting interaction observed in the study was to take the floor interface as the associated input interface. The participant chose to drag his feet in a path with the shape he expected.

8.1.2.2 Adding visual aids

Based on users' feedback, when manipulating the system, the accuracy was the primary concern. Participants would get anxious when they could not see the real-time feedback of the system. To solve this problem, applying visual aids was one positive method. For example, projections could project the special effects on activated cubes when users perform the selecting gesture, or project out the expected formed pattern. Apart from this method, one participant used his shadow to demonstrate the pattern he wanted in the study. Concerning this, the visual aids could be created with a bundle of light and people's shadow would serve as a real-time instruction.

8.1.2.3 Gestures set

The gestures set is essential for the interaction design because with that, researchers could investigate people's agreement on the set and designers could make a better design. Since the detailed performances of gestures sets were not evaluated, in this sector, I would provide strategies to create the set. First of all, there were three basic operations people would perform with the system: draw the shape, transform the shape and remove the shape.

For the first operation, shape drawing, one group of people would prefer to use fingers to draw the outline of the pattern. The second group would try to draw the path. Others would divide the shape into multiple rectangles and point to the two ends of rectangles' diagonals. After the drawing session, participants would either wait for the cubes to pop out or use extra commands like voice or double-tap to instruct the motion.

When participants were required to transform a specific shape, there were two ways for them to target that shape. One was to tap on any cube belonged to the shape, while the other one was to get close to that shape to perform commands. After activating the expected shape, people would do associated gestures.

As for the remove gestures, volunteers were likely to make the one-hand wipe gestures in the distance or press the cubes back when they were close to the system. Most people would prefer to make two-hand swipe gestures or have a clear button if there were multiple shapes in the system.

8.2 Limitation

In the elicitation study, I recruited 20 people to participate, and the number was referred to previous work. However, in the study, people would likely to be affected by their inertia thinking, which means they would probably adopt the same interaction without thinking in similar tasks. In view of this, the number may not be enough.

Also, because the purpose of the study was to understand the interaction. In other words, the results of the study were unpredictable. Hence, I used the projection as a low-fidelity set up to mimic the actual usage scenes. Nonetheless, it may have an influence on people's interaction. In the subsequent studies, a prototype with high fidelity should be tested. Additionally, every component was in the shape of a cube rather than other shapes. I did not study whether the shape would affect the interaction. Last but not least, in the study, there were 13 tasks, and I repeated every task for four times in different zones and with different cubes. There were more usage occasions that could be tested, and the cubes' sizes could be more diverse.

8.3 Future Work

In the project, I investigated how people would like to interact with shape-changing wall systems and what they would prefer to get as the feedback. 20 participants were recruited to interact with the interface projected on the wall. To further the study, more participants should be called up, and a relatively high-fidelity mock-up is to be tested. A complete set of operation process would be assessed, including form furniture of the particular shape, transform it, use the furniture, and put it back.

Furthermore, a detailed performance evaluation of different types of interaction is crucial. For example, in order to understand how participants would use different gestures to complete all the tasks, taxonomies of surface gestures and in-air gestures are required. Also, user-defined gesture set is necessary to create, and a further quantitative agreement test needs to be done.

In this study, I used blocks as the basic components of the system in the study, and to compare the impact that shapes have on interaction, other shapes should be tested as well, like rods. Similarly, two sizes of cubes were studied. In the future, more sizes of components need to be investigated to explore the optimum size. Moreover, how the height and length of the full interface effect the interaction deserve to be studied.

9.CHAPTER 8: APPENDIX

A chi-squared test code sample in R for analysing the distribution of different types of interaction in interacting with two sizes:

```
sizeOver <- read.csv("sizeOver.csv", row.names = 1)
soview <- as.matrix(t(sizeOver))

PlotM <- function(Z) {
  m <- ncol(Z);
  n <- nrow(Z);
  MM <- matrix(0,m,n);
  MM[1:m,] <- t(Z[,1:m][n:1,]);
}

sooview <- as.table(PlotM(soview))

chisq.test(sooview)
assoc(sooview,
      shade = TRUE)
```

A heatmap generating code sample in R:

```
library(RColorBrewer)
library(gplots)
library(heatmap.plus)
x <- read.csv("InteractionCSV.csv")
Smaller <- x[grep("Smaller", row.names(x)),]
y <- data.matrix(Smaller)
coul = colorRampPalette(brewer.pal(10,"RdBu"))(20)
heatmap.2(y,
          main = "Interaction Type - Smaller Cubes",
          scale = "row",
          col = coul,
          trace = "none",
          margins = c(5,10),
          cexRow = 0.7,
          Rowv = FALSE,
          Colv = FALSE
          )
```

Arudino code to control the servo:

```
#include <Servo.h>

Servo myservo;
int pos = 0;
int Button = 12;
int flag = 0;

void setup() {
  myservo.attach(7);
  Serial.begin(9600);
  pinMode(Button, INPUT);
}

void loop() {
  if ( digitalRead(Button) == HIGH ) {
    delay(2);
    if( flag == 0 ) {
      clockwise();
    } else {
      anticlockwise();
    }
    flag = 1-flag;
  }
}

void clockwise() {
  Serial.println("clockwise");
  for(pos = 0; pos <= 180; pos+=1) {
    myservo.write(pos);
    delay(15);
  }
  delay(500);
}

void anticlockwise() {
  Serial.println("counterclockwise");
  for(pos = 180; pos >= 0; pos-=1) {
    myservo.write(pos);
    delay(15);
  }
  delay(500);
}
```

Unity Code to form a container in the centre of the display:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System;

public class CreateCubes : MonoBehaviour
{
    public int number;
    public GameObject[] selectorArr;
    public GameObject[] toReturnArr;
    public GameObject selector;
    int returnCount = 0;
    int count = 0;
    float timer = 0;

    void Start() {
        selectorArr = new GameObject[number * number];
        toReturnArr = new GameObject[number * number];
        for (int i = 0; i < number; i++) {
            for (int j = 0; j < number; j++) {
                GameObject cube = Instantiate(selector, new Vector3((float)i * 
1.05f, -(float)j * 1.05f, 0), Quaternion.identity) as GameObject;
                if ((i >= 40 && i <= 44 && j >=50 && j <= 69) || (i >= 75 && i <= 
79 && j >=50 && j <= 69) || (j >=65 && j <= 69 && i >= 45 && i <= 75)) {
                    selectorArr[count] = cube;
                    count++;
                }
            }
        }
    }

    void Update() {
        timer += Time.deltaTime;
        if (timer >= 2 && timer < 3.5) {
            for (int i =0; i < returnCount; i++) {
                toReturnArr[i].transform.Translate(Vector3.forward * 0.05f);
            }
        }
        if (timer >= 5 && timer < 7.5) {
            for (int i = 0; i < count; i++) {
                selectorArr[i].transform.Translate(Vector3.forward * -0.05f);
            }
        }
    }
}
```

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